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# MATERIALS *and* PROCESSES

EDITED BY  
**JAMES F. YOUNG**  
*Engineering General Division  
General Electric Company*

*Eighth Printing*

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TO  
DR. A. R. STEVENSON, JR.



## PREFACE

This book has been written to present in one volume a broad study of the materials and manufacturing processes employed by the design engineer, and thus to provide information directly useful in the selection of materials for design. The book is intended for convenient reference and for textbook use. It has therefore been organized for ease in classroom presentation and in such a manner as, it is hoped, will give the practicing engineer or designer an over-all picture of the subjects discussed.

The problem of selecting the material for a piece of apparatus is no easy matter. One's first attempt at selection proves this quite convincingly. Plenty of information is available, but the real task is to find and evaluate that which has a bearing on the design. It is reasonable to assume that if a material has the properties required in service, it is suitable; and so it may be selected. It soon becomes clear, however, that *the* material also must be available in the right form, and be such that it lends itself better than others to the available and desired method of processing. In addition, the over-all cost, including both that of the material and of fabricating it, should represent the maximum value per dollar expended. And this combination can be obtained only when the product is both proportioned with respect to the material to be used and detailed to accommodate the method of processing.

The young engineer's training for design, which is largely obtained through working with more experienced engineers, should be preceded by some study of metallic and nonmetallic materials and of manufacturing methods. However, much of the available information on these subjects is not presented to suit the requirements of the design engineer. Data on metallic materials are presented largely from the metallurgist's viewpoint, and information on manufacturing methods usually tells how to accomplish the process and how to operate the equipment used. These approaches leave a rather broad gap in the design problem, a gap which it is hoped this book will bridge.

This textbook considers chiefly the materials and processes used in manufacturing electromechanical products. Sufficient metallurgy is included to enable the engineer to understand heat treating practice and the effects of various processes on metallic materials. In the discussion

of processes, enough detail for understanding the basic nature of each process is given; but — throughout — emphasis is laid on so designing the products that they can be easily processed. Materials and processes used only in building construction are not considered. Material-specifications systems and data have been left out also because of their changing nature and the impossibility of covering adequately all sources of supply.

Many of the chapters have been written from lectures given in a general course in materials and processes conducted in the Advanced Engineering program of the General Electric Company. The editor is indebted to the many engineers whose lectures and papers have been used in the preparation of this book, and, in so far as practicable, their names appear at the head of those chapters prepared from their lectures or incorporating their work. The editor also wishes to express his appreciation to Dr. A. R. Stevenson, Jr., to whom this book is dedicated, for the opportunity of preparing the book and for his encouragement; to Mr. E. E. Parker, Mr. E. R. Boynton, and Mr. J. E. Ryan, who served as the first supervisors of the general course and laid out the early lectures; to Mr. T. S. Fuller and Mr. E. R. Parker for their helpful suggestions and consultation; and to Miss F. E. Rist for her patience and good nature in typing the manuscript and in proofreading.

J. F. YOUNG

SCHENECTADY, NEW YORK  
*January, 1944*

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## PART I. MATERIALS

### CHAPTER I THE NATURE OF PURE METALS

**1.1. Introduction.** There are approximately forty chemical elements of commercial importance which may be classed as *metals*. They are distinguished from nonmetallic elements by *metallic properties* such as good heat conductivity, good electrical conductivity, characteristic luster, and the ability to be permanently deformed to some degree without fracture.

All the common metals are solid at normal (room) temperature except mercury, which is a liquid. They are all some shade of silver-gray except copper, which is red, and gold, which is yellow. All of them form alloys, as will be discussed in Chapter II, and both the metals and the alloys possess metallic properties and are classed as *metallic materials*.

Only copper, the precious metals, and small amounts of iron (meteorites) occur in the free state in nature. The other metals are always found chemically combined with other elements as ores. The science (and art) of extracting metals from their ores, refining or purifying them, and adapting them to use is known as *metallurgy*. Sometimes this broad field is considered as having two main divisions: process metallurgy and physical metallurgy. These divisions are not clearly defined, but it is usually agreed that process metallurgy deals with the purification and reduction of ores, and the refining, working and heat treatment of the metallic materials obtained. Physical metallurgy covers the study of the fundamental nature of metallic materials for the purpose of explaining the various phenomena associated with process metallurgy. The theories resulting from the work of the physical metallurgist point the way for the development of new materials and processing techniques on which progress in the many branches of engineering relies heavily.

An understanding of physical metallurgy is necessary to both the designer and the manufacturer — to the designer so that he may be

guided in the selection and effective utilization of materials; and to the manufacturer so he will appreciate the purpose and exactness of processing techniques, and avoid waste and spoilage due to misuse of material. This chapter, and the next on Alloys, are therefore devoted to a discussion of the fundamentals of physical metallurgy. They form the background on which the remaining study of metallic materials and processes will be based.

**1.2. The Structure of Metals. *The Atom.*** In chemistry, all matter is said to be made up of molecules, each molecule containing a number of smaller units called *atoms* which are present in some arrangement characteristic of the molecule. The functioning units in metals, however, are found to be monatomic, that is, single atoms. For that reason, metallurgists consider the atom to be the fundamental unit of metallic material, and the term "molecule" is not used in describing metallic structure.

For most purposes in physical metallurgy, it is convenient to think of the atom as a functioning unit of very small size, shaped something like a ball. Occasionally it is helpful to use the physicists' picture of the atom as being composed of a heavy nucleus, which contains most of the mass, and a cloud of electrons which forms the ball-like exterior. These electrons are in motion in special orbits, the motion being changed in some manner by changes in temperature, and the orbits being somewhat modified by the presence of other atoms.

**Liquid Metal.** In liquid metals the atoms may be considered as constantly in random motion throughout the volume of liquid and restrained in their motion only by their neighbors and by the walls of the containing vessel. The higher the temperature, the more rapid the motion, until at the boiling point the atoms break the surface tension forces and leave the surface of the liquid as vapor. Most metals boil at temperatures above those used in common metallurgical practices, but such metals as mercury, zinc, cadmium, and arsenic are exceptions. The boiling point of mercury is low enough that the properties of its vapor may be successfully utilized for power generation in a vapor turbine. Zinc vaporizes at a higher temperature than mercury, but distillation of zinc vapor as a method of refining the metal is possible on a commercial scale.

**Solidification.** As a liquid metal cools, the motion of the atoms becomes slower and slower until the *freezing point* is reached. At this temperature, the *random* motion of the atoms stops, and they take fixed locations with regard to one another, forming a solid metal. All the atomic motion does not cease as a result of solidification, but that motion which persists is confined to vibration within these fixed loca-

tions. A further decrease in temperature will cause some modification of this atomic vibration in keeping with a lower energy state.

If the heat removed during freezing is removed at a constant rate, the cooling curve (temperature vs. time) will be similar to that shown in Fig. 1.1. Cooling of the liquid is indicated by the line from point 1 to point 2. At point 2 freezing begins, and constant temperature is maintained until freezing is complete at point 3. Continuing the removal of heat from the now solid metal causes the drop in temperature 3 to 4. Note that during the time interval 2-3, the temperature remained constant although heat was being removed at a constant rate. The heat energy given up during this interval is called the latent heat of fusion. It is supplied by the atoms as they take up fixed positions and lose their kinetic energy of random motion.

*Solid Metal.* The atoms of the solid metal are held together by interatomic forces due mainly to the electrons. These forces are greater in some directions than in others; consequently, the atoms arrange themselves in geometric patterns called *space lattices*. Each metal always forms its own type of atomic space lattice when allowed to cool from the molten state; and since the lattices are orderly in nature, it is possible to find in them a simple configuration of a few atoms which is repeated over and over again. Such simple configurations are called *unit cells*.

Although there are fourteen known lattice configurations for metals, most metals crystallize according to only three types. They are body-centered cubic, face-centered cubic, and close-packed hexagonal. Table 1.1 gives a list of several metals and the lattice types to which they belong at room temperature.

TABLE 1.1

<i>Body-Centered Cubic</i>	<i>Face-Centered Cubic</i>	<i>Close-Packed Hexagonal</i>
Chromium	Aluminum	Beryllium
Iron	Copper	Cobalt
Molybdenum	Gold	Magnesium
Tantalum	Lead	Titanium
Tungsten	Nickel	Zinc
Vanadium	Platinum	Zirconium
	Silver	

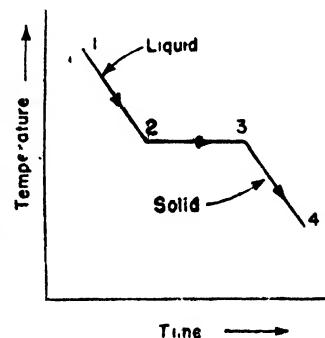
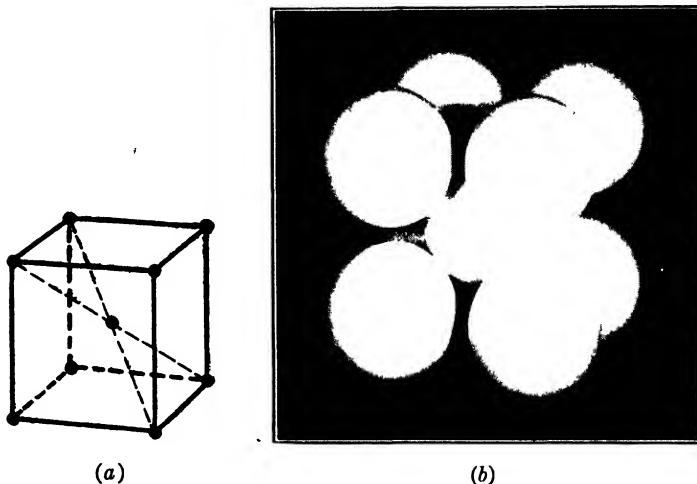


FIG. 1.1. Cooling curve for the freezing of a pure metal.

The unit cell of the body-centered cubic structure has an atom in each corner of a cube, and one in the center as illustrated in Fig. 1.2a. The atoms should not be pictured as concentrated at these positions, but rather as having their centers of activity located there, and their spheres of influence being packed close together as illustrated by the model made from ping pong balls, Fig. 1.2b.



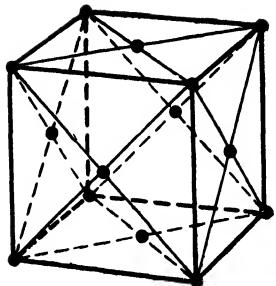
**FIG. 1.2.** Unit cell of the body-centered cubic structure.

- (a) Sketch showing location of atom centers.
- (b) Ping-pong ball model.

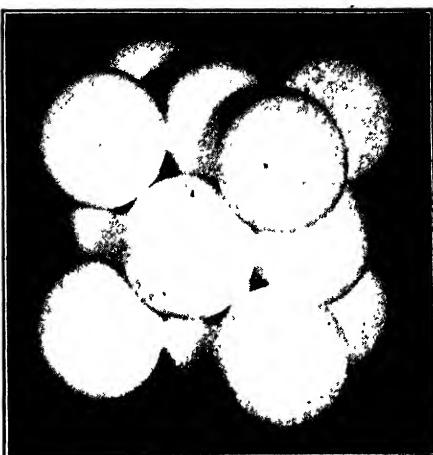
The unit cell of the face-centered cubic structure has, as the name indicates, an atom located in the center of each face, as well as one in each corner of a cube, but none at the center. This arrangement and the corresponding ping pong ball model are illustrated in Fig. 1.3 (a and b).

The third common lattice form is the close-packed hexagonal structure shown in Fig. 1.4a. This unit cell is a hexagonal prism with atoms in the corners and the center of the hexagons formed by the top and bottom planes, and three atoms equally spaced in the center of the prism. The model of this unit cell, Fig. 1.4b, was constructed without the top plane so the packing of the three center atoms could be shown.

These unit cells may be considered as the effective building blocks of which the solid metal is built, much the same as bricks are the building blocks of which walls are built. In the solid metal, the unit cells are associated in such a way that the atoms are shared by the neighboring unit cells. In a cubic lattice, for example, eight neighboring cells



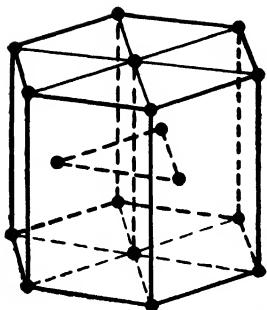
(a)



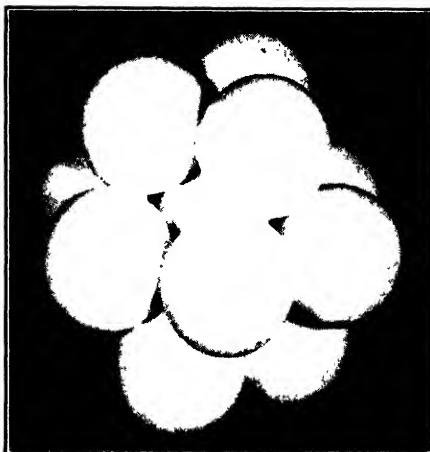
(b)

**FIG. 1.3.** Unit cell of the face-centered cubic structure.

- (a) Sketch showing location of atom centers.
- (b) Ping-pong ball model.



(a)



(b)

**FIG. 1.4.** Unit cell of the close-packed hexagonal structure.

- (a) Sketch showing location of atom centers.
- (b) Ping-pong ball model with top hexagonal plane removed and an extra cluster of three center atoms below.

share a corner atom. The unit cell size is characteristic of the metal, but all are very small (on the order of  $3 \times 10^{-8}$  cm on an edge). Millions of them placed side by side and extending in all directions are required to form a *crystal* of metal.

The continuous orderly arrangement of atoms in a crystal makes it possible to pass imaginary planes through common atoms of a large number of unit cells. The cube plane, for instance, is parallel to one face of a cubic unit cell and contains cube face atoms of many connected unit cells. Planes passed through the crystal so as to contain common atoms of many unit cells are referred to in general as atomic planes.

**1.3. Allotropic Modifications.** A number of metals exist in one crystal lattice form over a range of temperature, but at a certain critical temperature the lattice form changes to another type which is stable over another temperature range. Such metals are said to be *allotropic*, and the change from one type of crystal lattice to another is referred to as an *allotropic change*. These different lattice forms are, of course, identical by chemical analysis, but they usually possess widely different physical properties.

Iron is the most familiar example of an allotropic metal. In Table 1.1 it is listed as having a body-centered cubic unit cell. This type of structure is retained up to 910 C, but above that temperature the iron changes to a face-centered cubic type of unit cell. In turn, this structure changes back to the body-centered cubic type at 1400 C and the metal melts at 1535 C.

**1.4. The Grain Structure of Metals.** During solidification, the atoms of the liquid metal start to freeze by forming a unit cell which acts as a nucleus for further solidification. If no other nuclei form, this single unit cell will grow continuously as atoms of the liquid metal attach themselves to it, gradually building up the space lattice until all the metal has solidified. If this occurs, the metal will be a single crystal in which all the atomic planes are parallel to those of the original unit cell which acted as a nucleus. Such single crystals have been produced in large sizes, e.g., several inches in diameter and a foot long. With the usual rates of cooling, however, the solidified metal is generally composed of thousands of crystals, each different in orientation from its neighbors. Each of these crystals started from a unit cell and grew until it met its neighbors, which were of course growing from other nuclei. The number of crystals (more commonly called *grains* in metals) that form depends jointly on the rate at which the nuclei form and the rate of grain growth. The more nuclei forming simultaneously from the liquid, the greater the number of grains, that is, the smaller the *grain size*. Again, the slower the rate of grain growth, the smaller the

grain size, provided the rate of nuclei formation is moderate. It is conceivable that the rate of grain growth could be so high that regardless of the rate at which nuclei form, the whole melt would solidify in a few grains. But the rate of grain growth is usually low enough so that the rate of nucleation has a predominant influence on the grain size. The rate of cooling, in turn, determines the rate of nucleation; rapid cooling therefore usually results in the formation of many small grains, and slow cooling produces fewer but larger grains.

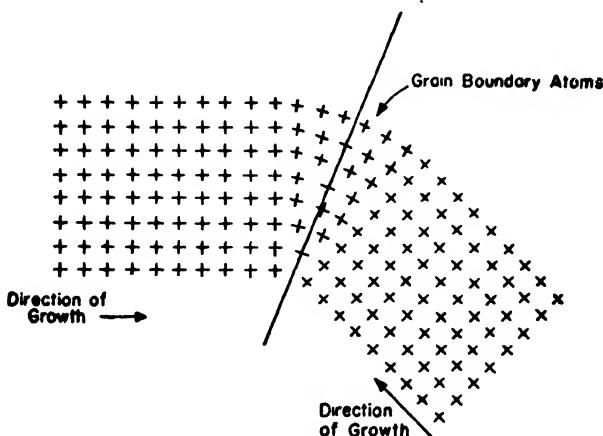


FIG. 1.5. Schematic diagram of the arrangement of atoms at a grain boundary. The crosses indicate atom positions.

When two adjacent grains grow together during freezing, the atoms of the last liquid to solidify are mutually attracted to both grains. Since the orientations of the two grains differ (otherwise they would unite and become one), these atoms cannot form on either lattice, but must occupy compromise positions as shown in Fig. 1.5. The region between grains which contains these displaced atoms is called the *grain boundary*. Grain boundaries interrupt the continuity of the lattice planes and greatly increase the resistance of the metal to cold deformation;<sup>1</sup> hence, a small grain size is desirable in a metal which must support an applied load.

**1.5. Microscopic Analysis. Optical Microscope:** Most grains in metals are too small to be seen by the naked eye, so they are usually magnified by an optical microscope for the purpose of study. The image visible in the microscope may be photographed to record the appearance of the structure for subsequent analysis. Such photographs

<sup>1</sup> Deformation is discussed more completely under the section on cold work.

are called photomicrographs. Although it is not essential that the engineer be able to take these photomicrographs, a proper interpretation of them will help him to visualize the grain structure of a metal and to understand the illustrations which appear in later sections. It will also enhance his ability to work with the metallurgist. A short discussion of microscopic analysis is therefore appropriate at this point.

Before specimens of metal can be microscopically examined, they must be polished to an optical flat so that the whole section under the microscope can be enlarged in focus. A large magnification is involved and this, together with the work associated with the polishing operation, makes it best to use small specimens. There seems to be practically no limit to the minimum size used, for samples as small as a few micro-inches across have been examined successfully. The maximum size, however, usually does not exceed one inch in width (either square or round in cross-section) and three-fourths inch in length. After the sample of the region of interest is cut within these limits, it is mounted in a piece of plastic or other suitable mounting medium and the polishing operation is begun. This operation consists of three steps: (a) grinding, usually by emery or carborundum wheels, (b) rough polishing by fine emery papers to remove the markings or scratches left by the emery or carborundum wheels, (c) fine polishing or lapping with a very fine polishing powder to remove the fine scratches left by the rough polishing. Usually fine wet alumina powder is used on rotating disks covered with broadcloth or felt.

The polishing operation leaves the specimen with a mirrorlike finish and if it is examined under the microscope, it will show merely a mirror reflection of the light source. If inclusions or cavities are present in the surface of the specimen, they will be distinguishable because they reflect light differently than the polished surface.

In order to distinguish individual grains, the polished surface of the specimen is etched with a suitable reagent. Several of the reagents used attack the grains more rapidly in some directions than in others, and so the orientation of the grains with respect to the polished surface will make a difference in the degree it is attacked. As a result, the originally flat surface, when etched, may have different "levels" for grains of different orientations, somewhat as shown in Fig. 1.6a. In pure metals, the exposed surface of each grain is usually optically flat (that is, the imperfections are smaller than the wave length of light), but they may be "rough" as indicated in Fig. 1.6b. The roughness depends upon the reagent and the grain orientation. For some metals a reagent may be chosen which will attack the grain boundaries more rapidly than the center of the grains, and by controlling the degree of attack, tiny

"valleys" may be produced at the grain boundaries before the center of the grain is appreciably affected. This effect is illustrated in Fig. 1.6c.

The grain boundaries may be detected on any of these surfaces when the specimen is viewed with the microscope. Briefly this may be explained as follows. The light from the microscope is directed perpendicularly to the surface of the specimen. If the etchant has produced a surface such as that shown in Fig. 1.6a, the light striking each grain will be reflected back into the microscope at nearly full intensity, and the grains will be uniformly white. The grain boundaries will be dark by contrast because the light striking them will be reflected outside the

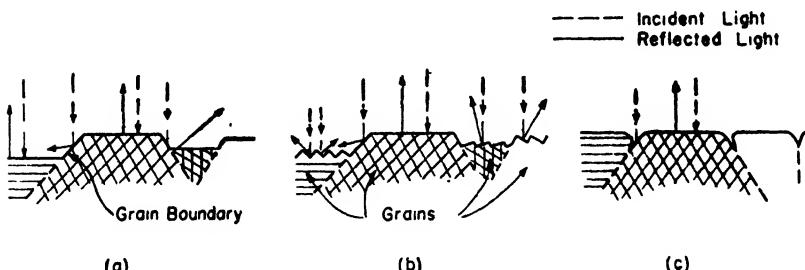


FIG. 1.6. Sketch showing the effects which may result from etching a polished surface, and the manner in which the etched material reflects incident light.

- (a) Grains attacked at different rates, grain surface optically flat.
- (b) Grains attacked at different rates, grain surface optically rough.
- (c) Grain boundaries attacked, grains almost unaffected.

microscope. The photomicrograph, Fig. 1.7, shows the grain structure at high magnification of a pure metal etched in this way. Note that the grains are not necessarily uniform in size or shape.

If the surface is like that shown in Fig. 1.6b, in which the surfaces of the grains are not optically flat, the grain boundaries will appear dark, as before, but the grains will be shaded from white to dark. The difference in shade of these grains is due to the relative amount of light that is reflected outside the microscope by the tiny roughened planes on the exposed surface of a grain.

The separate grains of a surface like the one shown in Fig. 1.6c will appear uniformly white because they are lightly etched. The grain boundaries will appear dark by contrast because the light striking them will be partially absorbed (as a result of multiple reflections) in the tiny "valleys" and partially reflected outside the microscope.

At present, the customary working range of the optical microscope is from 100 to approximately 2000 linear magnifications. It is frequently used at higher magnifications, however, for specific purposes.

**Electron Microscope.** The electron microscope is a recent development in which an electron beam instead of visible light is used for inspecting samples. The beam of electrons cannot be reflected from a metal surface, as is a light beam; consequently polished and etched metallographic specimens are examined by the use of a transfer technique. A thin film of plastic material (which is partially transparent to the electron beam) is cast on the surface of the etched specimen to

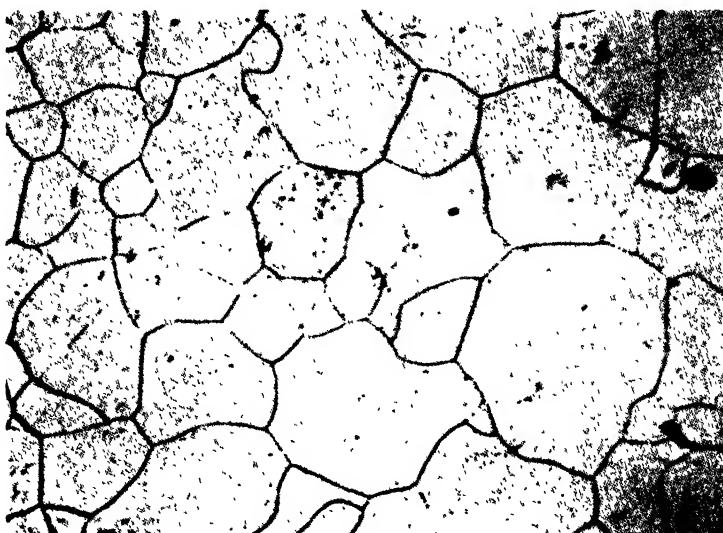


FIG. 1.7. Photomicrograph of pure iron (annealed) at approximately  $\times 100$ . Black lines indicate grain boundaries (Rosenhain).

take its contour on the contact side. This film remains flat on the free or top side. After it solidifies, it is stripped off the specimen and placed in the electron beam for examination. The electrons pass through the film, are diverged for magnification (by either electromagnetic or electrostatic fields), and finally fall on and expose a photographic plate.<sup>1</sup> For visual examination, a fluorescent screen is used in the place of the plate. Differences in levels produced by etching may be detected because the degree of transparency of the film varies with its thickness. This type of microscope shows promise for metallographic examination of transfers at magnifications up to 50,000 times.

**1.6. Refining and Forming Methods.** There are three ways in which metals are refined from their ores. They are (a) furnace reduction involving chemical reaction, (b) furnace reduction involving

<sup>1</sup> An electron-micrograph of an alloy is included in Chapter VI, Fig. 6.9.

condensation of vapor, and (c) electrolytic deposition from partially refined ore. Methods *b* and *c* are economically useful for only a few metals. Condensation from the vapor is used for refining mercury and zinc, and electrolytic deposition is used for refining aluminum, magnesium, copper, nickel, and some other metals.

The metals obtained by these methods of refinement may be molten, solid, or powdered. The first operation for putting them into form for their use may be either<sup>1</sup> (a) pressing and sintering metal powders, or, more commonly, (b) casting from the molten state into a suitable shape.

Pressing and sintering consists of pressing finely powdered metal into a mold of the desired shape, then heating the pressing in a non-oxidizing atmosphere to a high temperature to sinter or weld the particles together. The actual tonnage of metal prepared in this way is rather small and the applications rather specialized, but important. The process will be discussed in Chapter XIII.

By far the greater tonnage of metal produced is refined in a furnace and cast from the molten state. Some may be cast into the final form in which it will be used (for instance, in sand, die, and plaster of paris castings), but more frequently the metal is cast into ingots which are later rolled, forged, drawn, extruded, or hammered into various shapes such as large cylinders (forgings for turbine shafts, gun barrels, etc.), thin sheets, plates, rods, bars, rails, wires, etc. Metals furnished in these shapes are known broadly as *wrought* metals.

**1.7. Grain Structure in Castings.** Pure metals are frequently cast as ingots and wrought to final form, but very rarely are they used as cast shapes. Even so, it seems appropriate to include an explanation of how grain structures peculiar to castings are obtained.

In the above discussion of solidification, it was assumed that heat was removed uniformly from all the molten metal. Nuclei were then formed throughout the melt, and the grains tended to be of the same size and of nearly equal dimensions in all directions, and no special alignment was noticed. In a casting it is not possible to cool all the melt uniformly because the heat must be removed through the wall of the container or mold. This causes the metal in contact with the wall to freeze first, and solidification proceeds toward the center from nuclei formed in the vicinity of the walls.

If the number of nuclei formed is large, grain growth along the wall will result in many intersections, and the grain size in this direction will be small. The growth toward the center of the liquid is not apt to be restricted so much by intersection with other grains because the heat energy is being removed through the solid metal at the wall, and

<sup>1</sup> These methods apply also to alloys.

the nucleation in the liquid is therefore limited. As a result, when freezing is complete, the grains are very long in directions perpendicular to the walls of the container. Grains of this type are called *columnar* grains. This effect is most pronounced in chilled thick sections.

Columnar grain growth is particularly undesirable in ingots which have square corners because planes of weakness are established at the

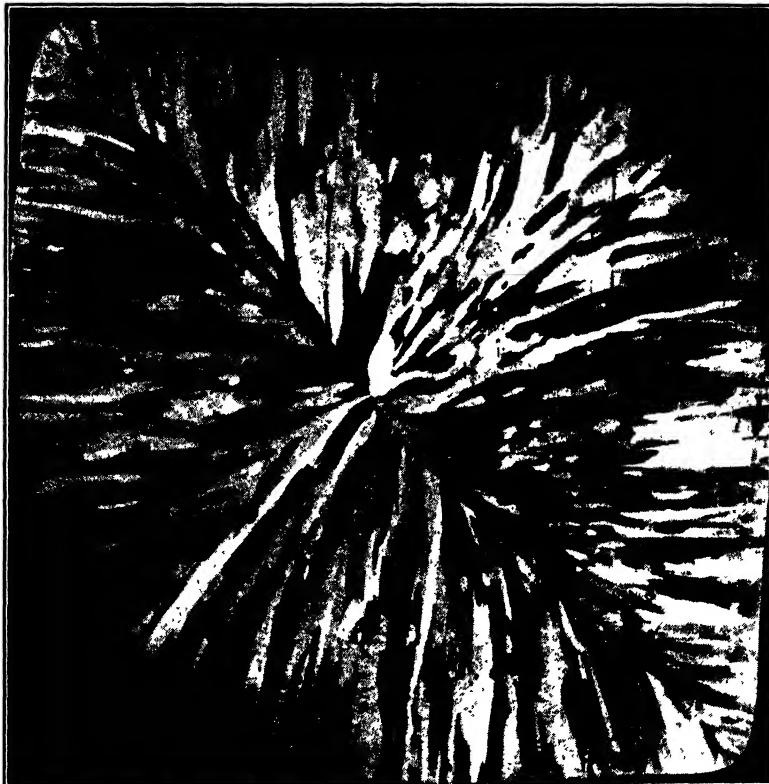


FIG. 1.8. Photograph of the cross-section of a copper ingot showing columnar grains (full size).

intersections of the columnar grains. These planes nearly bisect the corner angles, as shown in the photograph of the cross-section of a copper ingot, Fig. 1.8, and they reduce the mechanical strength of the ingot, making it susceptible to fracture during working. To minimize their formation, corrugated ingot molds with round corners are used. They cause the columnar grains to grow in all directions as illustrated schematically in Fig. 1.9.

This figure also illustrates another effect which occurs when metal is cast. The solid metal next to the mold contracts as it cools, and the change in volume is made up from metal of the still-liquid center of the casting. As the last metal solidifies, however, there is no more liquid to flow in and make up the contraction, and the *pipe* (the hollow section at the top of the casting) results. Various ingot forms have been used for different metals to obtain a shallow pipe.

If the cast metal is cooled slowly enough to give rather large grains at the center of the casting, these grains will be regular rather than columnar in shape. Within both types of grain shapes a structure known as *dendritic* or *pine tree structure* may occur. It occurs to some degree in most castings and is caused by preferred directional growth. Such growth is a natural characteristic of metals since it is easier to add atoms to the unit cells in certain planes than in others. During solidification, the more rapid growth in the preferred directions results in a skeleton crystal formation (the dendrite) which contains many interstices filled with melt. These liquid areas freeze last, and their contraction causes small regions of elastic strain which contribute to somewhat reduced ductility in the cast metal as compared with the same metal treated mechanically and thermally for highest ductility. The dendrites may also be outlined by impurities, or in the case of alloys, by other structural constituents present, and this is known as *dendritic segregation*.<sup>1</sup>

In casting pure metals and alloys into shapes or ingots, the columnar growth and formation of dendrites can be modified by choice of mold shape and control of grain size. It is emphasized, however, that the degree of occurrence of columnar grains and dendrites in alloy castings is largely a function of the composition of the alloy. Proper alloying and casting technique therefore render these effects subject to control.

**1.8. Cold Working.** Cold working refers to the act of permanently deforming a "cold" metal. The term "cold" is relative, and even room temperature may be "hot" for some metals (e.g., lead) as will be shown in the section dealing with recrystallization.

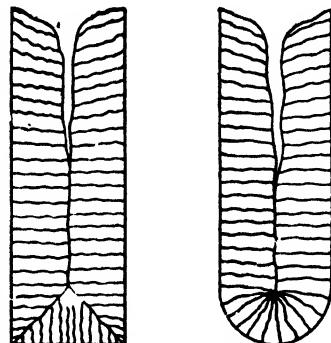


FIG. 1.9. Sketch showing the effect of square and round bottom corners on small ingot mold. Pipe is also shown.

<sup>1</sup> Dendritic segregation is illustrated in Fig. 2.5, Chapter II.

During cold working, two kinds of deformation occur. One is simply *elastic* distortion which is recoverable after removal of the load causing the disturbance. The other is *plastic* deformation, caused by loads greater than the limit of the elasticity of the metal. Such deformation is permanent and causes changes in shape and in the structure and properties of the metal. No cold working is done without causing this type of deformation.

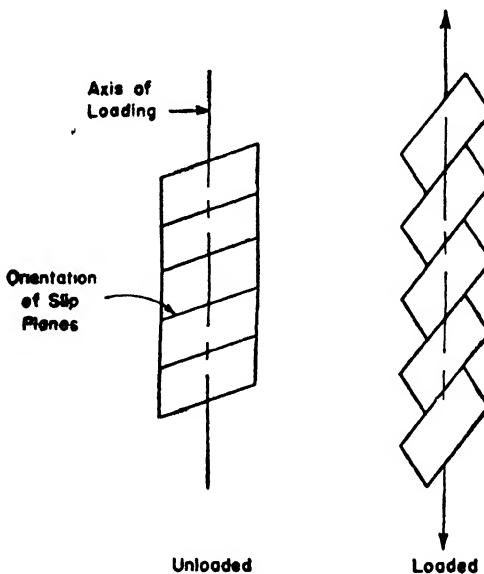


FIG. 1.10. Diagrammatic representation of slip in a single crystal.

*Plastic Deformation.* If a metal has been plastically deformed by cold work, the space lattice of each of its grains is partially distorted. Apparently the deformation has taken place by the slipping of parts of the grain over one another, similar to the sliding of cards in a deck. There are several combinations of planes of atoms and directions of slip that can function in a crystal, but the most favorable planes are those containing the greatest number of atoms, and most widely spaced in the grain. The slip takes place along these planes of dense atomic population even though they may not be aligned with the direction of loading, as shown in Fig. 1.10.

If the polished surface of a plastically deformed metal is viewed under a microscope, a series of parallel lines will be noticeable on each grain (see Fig. 1.11). These lines are slip lines or slip bands, and they are caused by a series of steps such as are shown in Fig. 1.10, but not so pronounced.

*Strain Hardening or Work Hardening.* As a metal is plastically deformed, it becomes stronger and a higher load is necessary to cause additional deformation. This phenomenon is known as *strain hardening* or *work hardening*. It is usually explained as follows:<sup>1</sup> X-ray dif-



FIG. 1.11. Photomicrograph of the pure iron specimen of Fig. 1.7 with a slight amount of cold work. Note the slip lines on each grain. Approximately  $\times 100$ . (Rosenhain)

fraction studies of plastically deformed crystal lattices show that the atoms in a deformed crystal are not arranged with absolute regularity as in the undeformed crystal, but instead, the atomic planes are roughened. Apparently this *roughness* is due to local distortion of the crystal lattice, and in consequence the lattice orientation varies slightly from point to point. The imperfections at the changes in lattice orientation appear to represent local regions of high elastic strain. As deformation proceeds, the irregularity of orientation increases, and greater force is required to cause the distorted planes of atoms to slip over one another. Thus the metal is hardened and strengthened as a result of strain or deformation.

*Grain Deformation and Preferred Orientation.* With extreme cold working, each grain will be elongated and its atomic planes change direction so that its orientation tends to line up with the direction of

<sup>1</sup> The mechanism described is generally accepted as representing the condition of a metal during deformation, but is not necessarily correct and may be modified as metallurgical knowledge improves.

working (see Fig. 1.12). Since the strength, magnetic characteristics, etc., of the crystals of some metals depend on the orientation of the crystal, this tendency to align the crystal lattices causes directional properties. For instance, the cold worked metal will possess better strength in the direction of alignment than in other directions. Directional properties are sometimes valuable, as in transformer laminations, and sometimes harmful, as in brackets made from sheet bent so the bent edge is parallel to the direction of working.



FIG. 1.12. Photomicrograph of copper cold worked to one-half original size. Note tendency for grain alignment. ( $\times 250$ )

**Fracture.** If the plastic deformation due to cold working or service loading is continued far enough, the metal will eventually fracture. The fracture occurs when the lattice distortion has progressed to the point at which the cohesion between atoms is finally broken. Fractures of a metal which result from excessive cold work or short-time loading (at temperatures too low for recrystallization) are therefore transcrystalline, that is, across the grains.

**1.9. Recrystallization.** After a metal has been plastically strained, as by cold work, it is subject to recrystallization if heated and held at a high enough temperature for a long enough time. By recrystallization is meant the formation of new, unstrained grains of nearly equal dimensions in all directions (equiaxed).

Three chief factors must be considered in recrystallization. They are time, temperature, and amount of previous cold plastic deformation. A general rule is: *the greater the amount of cold work done upon the metal, the lower the temperature at which recrystallization occurs.* Factors which tend to lower\* the recrystallization temperature are increased time at a

given temperature, smaller grain size prior to cold work, lower temperatures during cold work, and greater purity of the metal. Under the most favorable conditions there is a practical "lowest temperature" of recrystallization below which recrystallization will not occur except with a very long heating period. The practical, short-time "temperature of recrystallization" for some common pure metals is given in Table 1.2.

TABLE 1.2. PRACTICAL SHORT-TIME TEMPERATURE OF RECRYSTALLIZATION FOR SOME COMMON PURE METALS

Tungsten	1200 C	Silver	200 C
Tantalum	1000 C	Aluminum	150 C
Molybdenum	900 C	Magnesium	150 C
Nickel	600 C	Zinc	Room temperature
Iron	450 C	Cadmium	About room temperature
Platinum	450 C	Tin	About room temperature
Copper	200 C	Lead	Below room temperature
Gold	200 C		

One great value of recrystallization is that metals can be formed to a much greater extent and more economically by its use. In deep drawing operations, metals would become too hard to cold work and would fracture on further cold shaping if a recrystallization operation (annealing) were not used after a certain amount of cold work. This operation results in small, randomly oriented, equiaxed grains capable of being cold worked again. The deep drawing can thus be carried to completion by alternate straining and recrystallization.

Recrystallization may also be used in conjunction with cold working to refine coarse cast grain structure in an ingot.

*Annealing.* The term *annealing* is applied to the operations in which a metal is heated for the purpose of restoration of a fine, unstrained, equiaxed grain structure by recrystallization. Naturally the full anneal requires a temperature as high or somewhat higher than the recrystallization temperature, and time is a cooperative factor.

Stress relief may be accomplished by heating to temperatures below the temperature for recrystallization. This treatment tends to realign the atoms in the lattice, but does not cause formation of new grains. The grains' outline and mechanical strength are retained.

*Grain Growth.* Just after a metal has recrystallized, the grains are small and regular in shape. If the temperature is high enough or if the time at temperature is allowed to exceed the minimum required for recrystallization, the grains will grow. This growth is the result of a tendency to return to the most stable state, which is ultimately one

single large grain. The grains that are slightly larger than their neighbors grow at the expense of their neighbors until the small grains are all gone and only a few large grains remain.

The mechanism by which this growth occurs is thought to be as follows: The atoms in the grain boundaries are in a state of strain (high energy state). When the metal is heated to a high enough temperature, these atoms have enough mobility to align themselves with a crystal lattice. Because of the tendency to return to the most stable (low energy) state, they line up with the larger grain. The change from one grain to another may be thought of as movement of the boundary zone into the smaller grain, thus making the small grain smaller and the large grain larger. This process continues until the small grain is absorbed by the large grain.

For any temperature above the recrystallization temperature, normally there is a "practical maximum size" at which the grains will reach "equilibrium" and cease to grow appreciably no matter how long they are held at temperature. There are, however, certain cases of abnormal grain growth which occur as a result of applied or residual gradients of strain due to nonuniform cold work or nonuniform impurity distribution, and which permit growing very large single grains.

It should be noted that the grain structure of a pure metal which has no allotropic transformation, e.g., copper, cannot be refined without first cold working the metal to introduce some plastic strain. Even then, the metal must be heated to the recrystallization temperature or above, and heating discontinued before excessive grain growth occurs. Merely heating a pure metal which contains no plastic strain and is not allotropic will only cause grain growth, and not recrystallization.

**1.10. Hot Working.** Hot working is done in the same manner as cold working except at a high enough temperature so that recrystallization takes place simultaneously with straining, thus recrystallizing the metal even before it can effectively work harden.

There is, of course, the danger of grain growth at temperatures above the recrystallization temperature. If the hot working schedule is carried out in such a way that the metal reaches the recrystallization temperature on cooling about the same time that the plastic working is finished, the minimum grain size will result. If working is stopped at too high a temperature, grain growth will occur during cooling, thus tending to nullify the refining effect of the hot work. If, on the other hand, hot working is carried on too long and the metal cools below the recrystallization temperature, cold working would be effected.

The term "hot working" may apply to some operations where there is no heat applied at all (see Table 1.2). For instance, for lead, tin, and zinc, room temperature is at or above the recrystallization temperature, and these metals can be "hot worked" without the addition of heat. On the other hand, tungsten can be "cold worked" at a temperature of 1000 C, which is still below its recrystallization temperature.

The chief objective of hot working is economic and efficient shaping. Refinement of the grain is usually only a secondary objective.

*Fracture.* If the metal is fractured during hot working or during short-time loading at elevated temperatures, the fractures will not occur across the grain as for a short-time cold work fracture, but instead will follow the grain boundaries. This occurs because at the hot working temperature the grain boundaries are weaker than the grains and the metal fails when the cohesion between the atoms in the grain boundary is exceeded.

When the load has been applied for a short time, this intergranular type of fracture occurs only when the temperature is considerably above that for recrystallization. Such a fracture may also occur at temperatures nearer the recrystallization temperature with loads much less than the short-time strength if the load is applied for a long time. Apparently movement or flow of the atoms in the direction of the load takes place at most any temperature and load, and, at high temperature, when sufficient time is allowed, the elongation continues until failure occurs. This phenomenon is known as *creep*.

**1.11. Conclusion.** In this chapter, the basic characteristics of pure metals have been briefly considered. Most metals prepared commercially contain some small percentage of impurities, be it as little as 0.001 per cent. Although these impurities may have a great effect on the magnitude of the properties of the metal, it should be noted that the various types of grain structure and the characteristics such as cold work, slip, strain hardening, recrystallization, annealing, grain growth, hot working, fracture, and creep also define the behavior of these impure metals.

The information given has been based upon the most up-to-date theories in the science of metallurgy. All theories, however, are valid only so long as they explain the observed phenomena in a satisfactory manner. In the future, it can be expected that more satisfying explanations of some phenomena will be presented as more exact information on the nature of atomic structure is obtained. Meanwhile, the existing theory will form an adequate working tool.

**REVIEW QUESTIONS**

1. What is the crystal lattice of a solid metal, and what part of the lattice is called a unit cell?
2. Describe how separate grains are formed when a metal is solidified.
3. What two characteristics of the metal determine the number of grains that will form?
4. Iron is said to have several allotropic forms, e.g., alpha, gamma, and delta iron. What takes place in the iron when it changes from one allotropic form to another? How can this allotropic change be produced?
5. What are wrought metals?
6. Explain how columnar growth and dendritic segregation can occur.
7. Name the temperature that distinguishes hot working from cold working.
8. One strip of annealed metal is reduced by cold work from  $\frac{1}{4}$  in. to  $\frac{1}{8}$  in. in thickness and another strip of the same metal is reduced from  $\frac{1}{4}$  in. to  $\frac{3}{16}$  in. Which one would recrystallize at the lower temperature and which one would have the higher strength?
9. What two factors must be controlled if grain growth is to be limited when full annealing a piece of metal?
10. What operation must be used in conjunction with heat treatment to refine the grain size of a pure metal which has no allotropism?

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## CHAPTER II

### ALLOYS

By S. O. FISHER

**2.1. Introduction.** A substance which possesses metallic properties and is composed of two or more elements of which at least one is a metal is called an *alloy*. The metal present in the alloy in largest proportion is called the *base metal*, and all the other elements present, either metallic or nonmetallic, are called *alloying elements*. The presence of these alloying elements may result in a marked change in the properties of the base metal; so alloys have become of great importance to industry in providing materials which have a combination of properties that pure metals alone do not possess.

Many alloys can be measurably cold worked and hot worked, and given other treatments much the same as pure metals, but the magnitude of the response to such treatments is altered. For instance, the addition of an alloying element to a metal may raise or lower its recrystallization temperature or cause an increase or a decrease in the degree to which the metal will work harden. In addition, many alloys are "heat treatable"; that is, their mechanical properties can be altered considerably by heat treatments alone. The purpose of this chapter is to present a system for understanding the internal structure of alloys, and the effect of heat treatments on the structure.

**2.2. Mechanism of Alloying.** It was mentioned in Chapter I that metals are made up of crystals or grains in which the atoms are arranged in a definite and characteristic geometric configuration called a space lattice. In a pure metal, this space lattice is composed entirely of like atoms. In an alloy, two or more elements are present and the atoms of each element may be arranged in the space lattice in several different ways. For any alloy (such as one of copper and zinc, iron and carbon, or of any other system), three different relationships of the elements are possible, and a given alloy may consist wholly of one arrangement or of any combination of them. For simplicity, only binary (two element) systems will be used for examples.

**Case 1. The components can be insoluble in each other.** When the components of an alloy are insoluble in each other, the base metal and

the alloying element exist independently in an intimate mixture of grains, each element retaining its own identity, properties, and space lattice. A typical example is leaded copper in which small globules of lead are entrapped throughout a copper matrix, producing a free machining material.

*Case 2. The components can be soluble in each other, forming a solid solution.* In a solid solution, the type of space lattice of the base metal is retained although its properties may be altered considerably. The solid solutions may be of two types:



FIG. 2.1. Structure of Monel metal (67 Ni, 30 Cu, 3 Fe, Mn and impurities). The impurities show as black dots. ( $\times 250$ )

(a) *Substitutional.* In this type, alloying atoms *replace* base metal atoms in the space lattice of the latter, but are randomly distributed. An example is a solid solution of copper in nickel, such as Monel metal. The photomicrograph of Monel metal, Fig. 2.1, shows that the appearance of the solid solution is comparable to that of a pure metal. (Compare with Fig. 1.7.)

(b) *Interstitial.* This type occurs when the alloying atoms locate randomly in the spaces between the lattice planes of the base metal crystal. An example is a solid solution of carbon in iron.

A few metals are soluble in each other in all proportions in the solid

state, but most of them show limited solid solubility. The mechanism of solid solubility, however, remains the same whether or not the range of solubility of the metals is limited. These degrees of solubility are perhaps more clearly understood by comparison with alcohol-water and salt-water solutions. The two liquids, alcohol and water, are soluble in each other in all proportions. The solution of salt in water is an example of limited solubility. The salt is only soluble up to a fixed percentage, dependent on pressure and temperature; beyond that percentage, the salt will not dissolve and there will be two phases present, salt and a solution of salt in water.

*Case 3. The components can combine in a definite proportion to form an intermetallic compound in which the combining atoms occupy definitely related positions in the space lattice. The lattice is char-*

acteristic of the compound and is usually more complicated than for pure metals or solid solutions. This results in a lower order of symmetry with fewer planes of dense atomic population and gives these compounds great resistance to slip. Consequently, they are very hard and brittle, and if particles of such compounds are properly dispersed throughout a softer base metal, a high strength will result. There are many intermetallic compounds which are of importance because of this effect. Two examples are cementite,  $\text{Fe}_3\text{C}$ , which contributes greatly to the hardening and strengthening of steel, and copper aluminide,  $\text{CuAl}_2$ , which is effective in the hardening of certain aluminum base alloys.

**2.3. Phase Changes.** A phase is a portion of matter, homogeneous in the sense that its smallest *mechanically separable* parts are indistinguishable from one another. Thus, molten copper constitutes a phase, solid copper is a separate phase, but a mechanical mixture of lead and copper constitutes two phases.

In the previous chapter, it was mentioned that some pure metals are allotropic, i.e., they may exist in more than one form of space lattice. Iron, for example, is body-centered cubic at temperatures up to 910 C and face-centered cubic from 910 to 1400 C. Such an allotropic change is also called a phase change and can occur in alloys as well as in pure metals. In alloys, a solid phase may be a practically pure metal, a solid solution, or an intermetallic compound.

From these examples it will be noted that each phase has its own characteristic lattice structure, physical properties, chemical properties, etc. A change in phase therefore results in a change of properties.

**2.4. Diffusion.** To understand the mechanism of age hardening, heat treatment, case hardening, welding, or other changes in alloys in the solid state, it is necessary to understand the phenomenon of diffusion. Any metal after solidification has a definite space lattice in which each atom moves about within a fixed sphere of influence. Although it is true that atoms in a solid metal are less mobile than when in a liquid, they are still free to migrate from one point to another in the space lattice if given sufficient impetus. These movements are termed *diffusion*, and their rates are markedly affected by temperature; the higher the temperature, the more rapid the rate of diffusion.

The diffusion of atoms into a solid is illustrated in case carburizing. In this operation, a piece of low carbon steel (approximately 0.10 per cent carbon) is heated at 900 C in contact with charcoal or other carbon-bearing material. The surface of the steel becomes impregnated with carbon, forming a high-carbon steel case (approximately 1 per cent carbon), while the core remains a low-carbon steel. This result re-

quires diffusion of the carbon atoms into the steel at a temperature far below the melting point of either the carbon or the steel.

**2.5. Equilibrium, Phase, or Constitution Diagrams.** An equilibrium, phase, or constitution diagram states the quantity and composition of phases present in an alloy at a given temperature and pressure when the alloy is in complete equilibrium, i.e., when it has no further tendency to change structurally regardless of how long a time may elapse. Such a diagram is a summary of information on the behavior of all alloys of the system and on the possible combinations of each alloy's components during heating and cooling under conditions approaching equilibrium. Accelerated rates of heating or cooling may alter considerably the reactions which normally take place under near-equilibrium conditions.

In this section, characteristic equilibrium diagrams for binary alloys of the types met in practice will be discussed. Note that the components of these alloys will be either soluble or insoluble in the liquid state, and either completely soluble, partially soluble, insoluble, or combined as an intermetallic compound in the solid state.

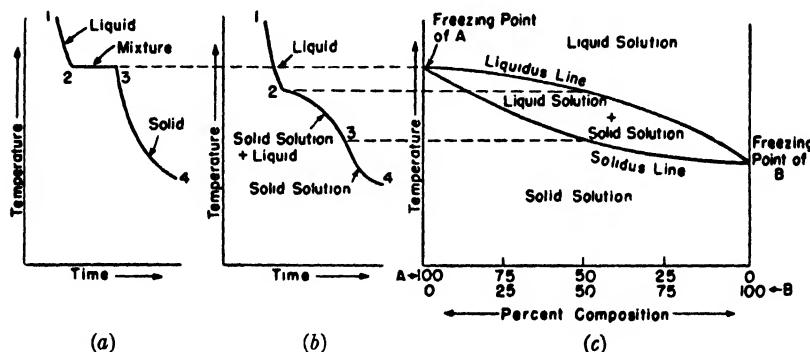


FIG. 2.2. Cooling curves and equilibrium diagram of a binary system showing complete solubility in the molten and the solid states.

- (a) Cooling curve of pure metal A.
- (b) Cooling curve of alloy 50% A, 50% B.
- (c) Equilibrium diagram.

**Case 1. Complete Solubility in Molten and Solid State.** In an alloy of this type, the addition of the alloying element alters the melting point considerably from that of the base metal, and causes the alloy to melt over a range of temperature rather than at a single temperature. This is illustrated in the constitution diagram, Fig. 2.2, for two metals, A and B.

The two cooling curves at the left of the constitution diagram show

how such diagrams are derived. Curve *a* depicts the solidification of pure metal *A*. It shows cooling of the liquid from 1 to 2, a thermal arrest 2 to 3 caused by the heat evolution of the metal as it gives up its latent heat of fusion, and 3 to 4 the cooling of the solidified pure metal *A*. The thermal arrest of pure metal *A* therefore corresponds to the melting point of *A* on the composition line 100 per cent *A*, zero per cent *B* on curve *c*.

Curve *b* depicts the solidification of an alloy of 50 per cent *A* and 50 per cent *B*. It shows cooling of the liquid from 1 to 2, continuous solidification of the solid solution (*A* + *B*) from 2 to 3 (which would constitute a mushy region of crystals of solid solution (*A* + *B*) and liquid), and cooling of the solid solution (*A* + *B*) from 3 to 4. Point 2, where solidification begins, is a point on the *liquidus* line; and point 3, where the solidification is complete, is a point on the *solidus* line at the composition 50 per cent *A*, 50 per cent *B* on curve *c*. From this it is evident that everything above the liquidus line is completely liquid and everything below the solidus line is completely solid. Between the liquidus and solidus lines, liquid and solid exist in equilibrium with each other.

The points on the cooling curves which were used in setting up this constitution diagram are those indicating solidification. Other phase changes, changes in the type of crystal structure, are the basis for those parts of diagrams which indicate changes in the alloy while in the solid state. A change in magnetic characteristics, for instance, may serve to indicate a phase change and may be helpful in setting up some diagrams.

As mentioned earlier, variations in the cooling rates may alter considerably the structure resulting from solidification of a solid solution alloy. The differences in structure can best be explained by considering the cooling of such an alloy when maintaining near-equilibrium conditions, and when the cooling rate greatly exceeds that required for equilibrium.

(a) *Solid Solution Solidification with Equilibrium.* Referring to Fig. 2.3, suppose a completely soluble alloy of some composition *X* is cooled very slowly from the molten state so as to approximate equilibrium conditions. When this alloy cools to the liquidus line at temperature *t*, liquid of composition *L* is in equilibrium with solid of composition *S*, and solidification begins. After further cooling to *t*<sub>1</sub>, some of the alloy has solidified and liquid *L*<sub>1</sub> is in equilibrium with this solid, all of which has a composition *S*<sub>1</sub>. At a temperature *t*<sub>2</sub> just above the solidus, a minute quantity of liquid *L*<sub>2</sub> is in equilibrium with solid *S*<sub>2</sub>. Finally at temperature *t*<sub>3</sub>, zero per cent liquid of composition *L*<sub>3</sub> is in equilibrium with 100 per cent solid of composition *S*<sub>3</sub> so that solidifica-

tion is complete. The solid  $S_3$  is chemically *uniform* and of exactly the same composition as the molten alloy  $X$ .

(b) *Coring.* However, alloys, as cast, usually *do not* have a uniform chemical composition. Instead, the composition may vary from the

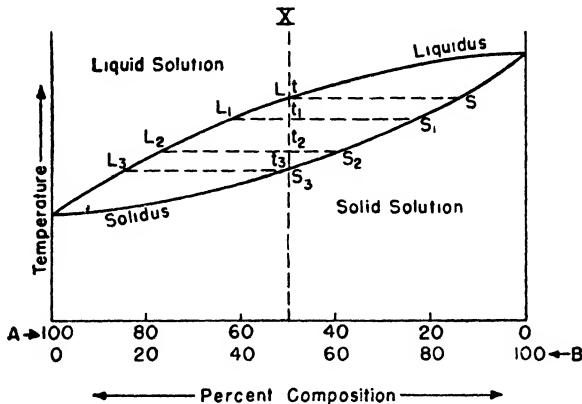


FIG. 2.3. Solidification of a solid solution alloy under equilibrium conditions.

center of a crystal to the outside of a crystal. This variation in composition in a single crystal or grain is known as *coring* and can be explained from the solid-solution diagram, Fig. 2.4.

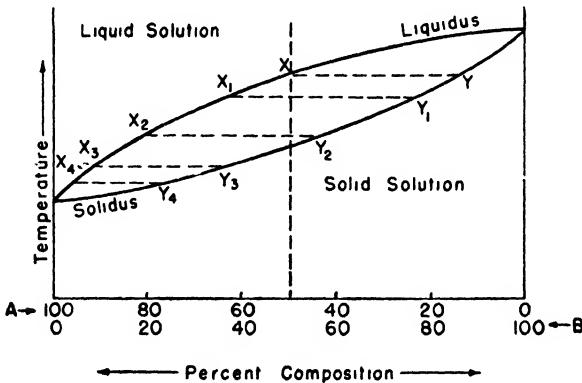


FIG. 2.4. Solidification of a solid solution alloy cooled at such a rate that equilibrium is not maintained.

Suppose an alloy of composition  $X$  is cooled from the molten state at such a rate that *equilibrium conditions are not maintained*. When it cools to the liquidus, the liquid is in equilibrium with the solid represented by  $Y$  on the solidus line and crystals of composition  $Y$  begin to

form. These crystals are richer in  $B$  than the original liquid so that their formation shifts the composition of the liquid toward 100%  $A$ , and at point  $t_1$  solid of composition  $Y_1$  begins to form. The liquid composition and the composition of the newly formed solid move farther toward the left as solidification continues, and the last liquid to solidify is

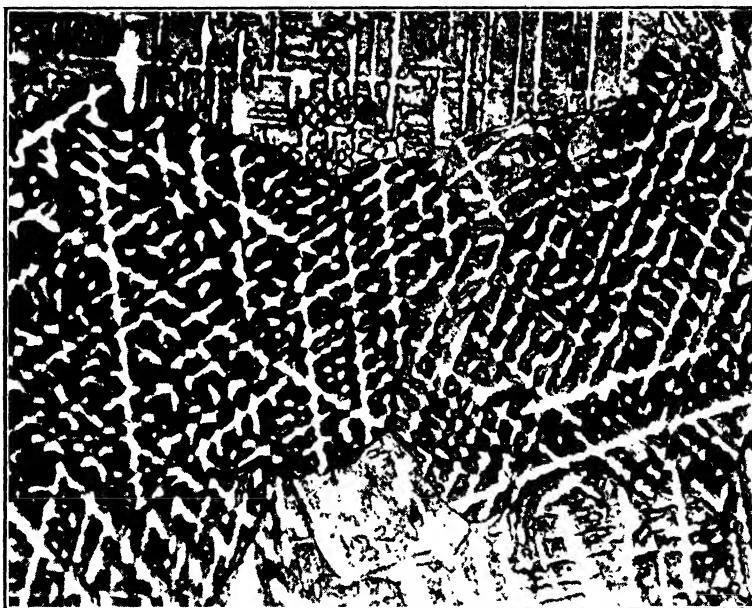


FIG. 2.5. Photomicrograph of a copper-nickel alloy (85 Cu, 15 Ni) showing cored dendritic structure. White areas are nickel-rich solid solution. Dark areas are copper-rich solid solution. ( $\times 100$ )

considerably poorer in  $B$  than was the original melt. During the solidification, the solid of lesser and lesser concentration of  $B$  is progressively added to the original crystal of composition  $Y$ , forming a *cored* crystal with  $Y$  composition in the center, grading into alloy rich in  $A$  for the last material to solidify.

The photomicrograph, Fig. 2.5, of a copper-nickel alloy (85 Cu, 15 Ni) illustrates a *cored* dendritic structure. It is a solid-solution alloy consisting of a *single phase*. The white areas are *nickel-rich solid solution*, and the dark areas are *copper-rich solid solution*. The etchant attacks the copper-rich material more rapidly than the nickel-rich solid solution so that the copper-rich areas appear dark, the nickel-rich white. The nickel-rich material has solidified first, and thus formed the skeleton of the dendrite and the copper-rich material then solidified in the

interstices of the nickel-rich skeleton core. When the core is the skeleton of a dendrite, as in Fig. 2.5, coring is usually called dendritic segregation.

Elimination of coring can be accomplished by causing diffusion of the atoms by heating to a suitable temperature for some time, or by a combination of working and heating of the alloy.

*Case 2. Soluble in the Molten State, Partly Soluble in Solid State.* When two metals are completely soluble in the molten state and only partly soluble in the solid state, the addition of one to the other usually lowers the freezing temperature of the melt. The intersection of the descending liquidus lines describes an alloy of the lowest freezing point of the system, which is called an *eutectic alloy*. The particular composition at which the eutectic point occurs is known as the eutectic composition.

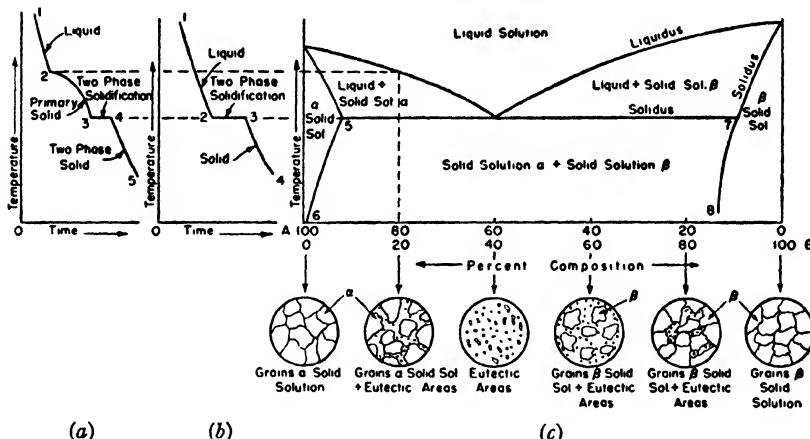


FIG. 2.6. Cooling curves and equilibrium diagram for a binary system completely soluble in the molten state, and partly soluble in the solid state.

- (a) Cooling curve of alloy 80% A, 20% B.
- (b) Cooling curve of alloy 60% A, 40% B.
- (c) Equilibrium diagram.

Again the equilibrium diagram can be derived from cooling curves of alloys of several different compositions (see Fig. 2.6). In cooling an alloy containing 80 per cent *A*, 20 per cent *B* (curve *a*), the cooling of the melt is represented by 1-2. From 2 to 3, solidification of "primary" crystals occurs. These crystals, as with the solid-solution alloy of Fig. 2.2, are a solid solution. They contain metal *B* dissolved in metal *A* and are denoted by  $\alpha$  (alpha) to distinguish them from the pure metal *A*. When the first primary crystals of  $\alpha$  solidify, the effective composition of the remaining liquid is shifted toward the eutectic. Further

cooling results in further solidification of  $\alpha$  crystals until finally all the remaining liquid is of the eutectic composition: 60 per cent *A*, 40 per cent *B*. All this liquid solidifies at one temperature (3-4 on curve *a*) as the alloy is cooled. The resulting structure of the alloy will be nearly 50 per cent primary crystals of  $\alpha$  and 50 per cent eutectic areas, although the alloy contains 80 per cent *A* and 20 per cent *B* by analysis. Further cooling of the now solid alloy is represented by 4-5.

If the freezing of an alloy containing 30 per cent *A* and 70 per cent *B* had been considered, the primary crystals would have been a solid solution of metal *A* in metal *B*. On Fig. 2.6, these crystals are denoted by  $\beta$  (beta) to distinguish them from pure metal *B*. Further cooling of this alloy results in more  $\beta$  crystals and also shifts the composition of the remaining melt toward the eutectic. As before, the last alloy to solidify will be of eutectic composition. The structure will consist of primary  $\beta$  crystals and eutectic areas.

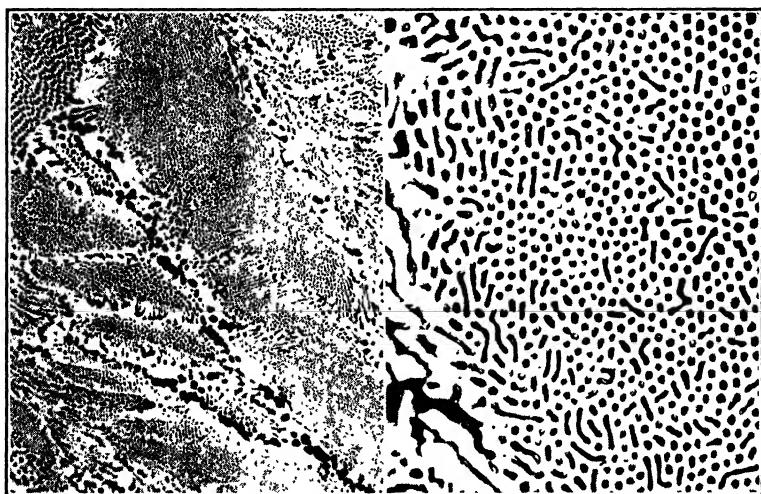


FIG. 2.7. Iron-carbon eutectic, specimen cooled very slowly from the melt. The dark areas are pearlite and the white matrix is cementite. Left  $\times 100$ . Right  $\times 500$ .

The cooling curve of the eutectic composition is illustrated in Fig. 2.6 (curve *b*). As the latent heat of fusion is removed from the molten alloy, line 2-3, the solid solutions  $\alpha$  and  $\beta$  form at practically the same time at a practically constant temperature. The pattern or arrangement of the mixed  $\alpha$  and  $\beta$  phases is dependent upon the alloy system and the rate of cooling from the melt. A photomicrograph of a typical eutectic structure is illustrated in Fig. 2.7.

After an alloy of the eutectic type has solidified, further cooling may

result in some change in the alloy. Just as the solubility of salt in water varies with temperature, so may the solubility of one metal in another metal vary with temperature even though these metals are in the solid state. Line 5-6 on the diagram shows decreasing solubility of *B* in  $\alpha$  and line 7-8 shows increasing solubility of *A* in  $\beta$  with decreasing temperature. If an alloy in the range 5-6 is cooled under near-equilibrium conditions, particles of  $\beta$  will precipitate from the  $\alpha$  solid solution. This type of solid-solution boundary is the basis for heat treatment of the *precipitation hardening alloys*.

While this particular diagram shows one decreasing-solubility and one increasing-solubility solid-solution field, other systems may have some other combination of these boundaries or even a vertical composition boundary for its solid-solution fields.

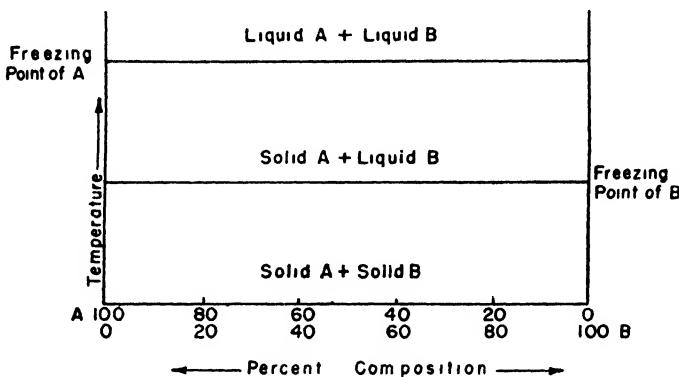


FIG. 2.8. Equilibrium diagram for a binary alloy system having complete insolubility in both the liquid and the solid state.

**Case 3. Complete Insolubility in Both the Liquid and the Solid State.** When two metals are completely insoluble in each other, each solidifies at its own freezing point regardless of the composition of the mixture. Fig. 2.8 indicates that any molten mixture of *A* and *B*, when cooled below the freezing point of *A*, would then consist of liquid *B* plus solid *A*. Cooling below the freezing point of *B* would result in solid *A* plus solid *B*. Thus in such an alloy, each metal retains its own space lattice, properties, and melting point.

**Case 4. Intermetallic Compounds.** Many binary systems of alloys contain one or more intermetallic compounds. The structure of these compounds was described in the section on the mechanism of alloying and will not be reviewed here, but it should be added that intermetallic compounds have a constant temperature of solidification.

The equilibrium diagram, Fig. 2.9, illustrates one type of alloy which

may form an intermetallic compound  $A_xB_y$ . There are two separate eutectic compositions,  $e_1$  and  $e_2$ . The simplest way to analyze an equilibrium diagram of this type is to consider it as two separate diagrams, one having  $A$  and the intermetallic compound  $A_xB_y$  as components, and the other having the intermetallic compound  $A_xB_y$  and  $B$  as components. In this example, there are two eutectic systems similar to that shown in Fig. 2.6.

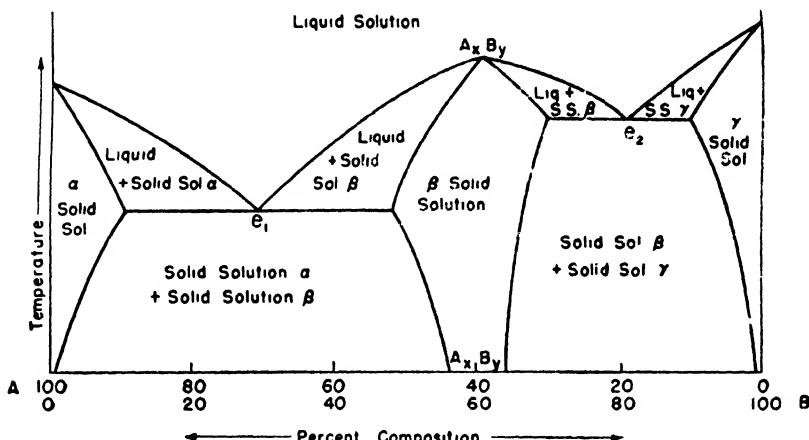


FIG. 2.9. Equilibrium diagram for a binary alloy system forming an intermetallic compound and two eutectic systems between the compound and the component metals. The solid solution fields  $\alpha$  and  $\gamma$  are shown large, indicating large solubility, but they are more commonly very narrow.

The equilibrium diagrams discussed in this section represent the most important liquid-solid reactions of alloys. They are fundamental to the known types of equilibrium diagrams.

**2.6. Precipitation Hardening Alloys.** There are many possible types of phase reactions in alloys in the solid state. Of these types, precipitation is one of the most important. It is the reaction which makes possible the strengthening and hardening of alloys of those systems in which there is a decrease in solid solubility with decreasing temperature. Such a system may be represented by the equilibrium diagram, Fig. 2.10 (similar to Fig. 2.6), where the decreasing solid solubility of  $B$  in  $\alpha$  is indicated by line 1-2.

An alloy of composition  $X$ , heated to a temperature  $t$  within the  $\alpha$  field and held until equilibrium conditions have been reached, will consist of the single phase,  $\alpha$ . If this single phase were rapidly cooled or quenched to room temperature so that equilibrium conditions could not be maintained, then  $B$  would be retained in a supersaturated solid

solution of  $\alpha$ . This solid solution is unstable and tends to reach equilibrium by precipitation of  $\beta$ . The precipitate acts on the slip planes of the alloy like sand or grit on an icy sidewalk, interrupting (or blocking) these slip planes so that easy slip is no longer possible. It appears there is an optimum size of precipitated particle because the growth of these particles is accompanied by first an increase and then a decrease in hardness and strength. When the solid solution  $\alpha$  is first quenched,

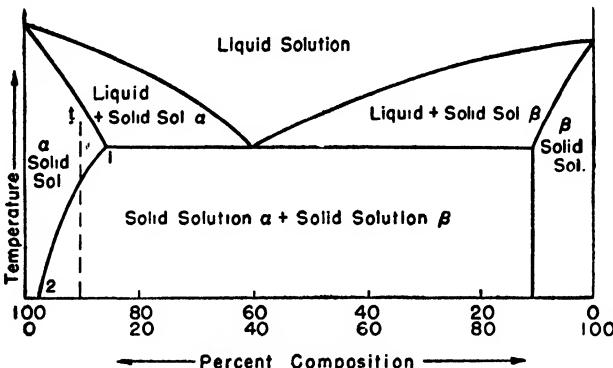


FIG. 2.10. Equilibrium diagram for a precipitation hardening system. Note the decrease in solid solubility with decreasing temperature (line 1-2).

there are no precipitated particles and the alloy is in its softest and most ductile condition. As precipitation begins, there is an increase in hardness and also in strength. This continues with continuing precipitation and growth of the particles until the optimum particle size is reached, after which further heating causes agglomeration of the precipitated particles and both hardness and strength decrease. Depending upon the alloy system, the precipitating phase may be a practically pure metal, another solid solution, or an intermetallic compound.

The process of heating and quenching to obtain a supersaturated solid solution is commonly referred to as *solution heat treatment*. The precipitation of the particles by reheating the quenched alloy is called *precipitation heat treatment* or *artificial aging*, or when such precipitation takes place at room temperature, *natural aging*.

There are many precipitation hardening alloys, but those having aluminum, copper, magnesium, nickel, or iron as the base metal are the most common.

**2.7. Heat Treatment of Steels.** Heat treatment of any metal or alloy consists of a program of heating and cooling to alter its characteristics and properties. Some of these are: strength, hardness, ductility, grain size, resistance to chemical corrosion, endurance limit,

shock resistance, conductivity, oxidation resistance, and stability for high temperature service.

Fundamentally, steel is an alloy of iron and the intermetallic compound, iron carbide, or cementite ( $\text{Fe}_3\text{C}$ ). The equilibrium diagram for these two components (see Fig. 2.11) may be likened to a eutectic system between a metal  $A$  and an intermetallic compound  $A_xB_y$  (see Fig. 2.9). The  $\gamma$  solid solution or austenitic field may be compared to

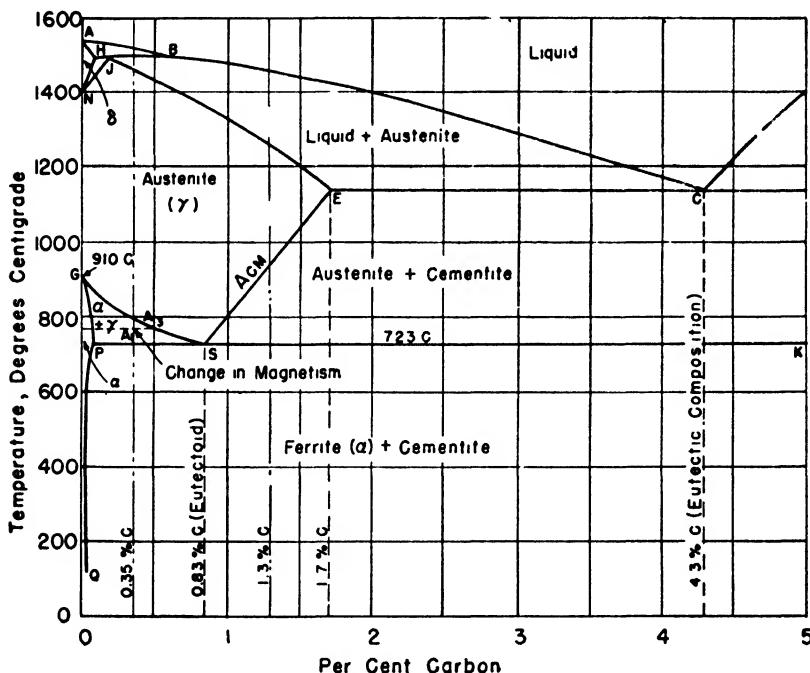


FIG. 2.11. Essential points of the iron-carbon equilibrium diagram. (For a more descriptive diagram, see Chapter VI, Fig. 6.1.)

the  $\alpha$  solid solution of the equilibrium diagram, Fig. 2.9. This  $\gamma$  solid solution is interrupted by the gamma-delta transformation at about 1400 C. The delta phase is of no importance in heat-treating practice and is mentioned only for the sake of completeness.

At 723 C and 0.83 per cent carbon, the  $\gamma$  solid solution is interrupted by a *eutectoid* reaction. What is a eutectoid? It will be recalled that a eutectic is the lowest *melting* point at which a *liquid solution* of two or more elements transforms into *two* solid phases. A eutectoid is the lowest *transformation* temperature at which a *solid solution* transforms into *two* solid phases.

*Structure and Properties of Steel.* Pure iron is only slightly harder and stronger than copper. It is the allotropy of iron which permits the range of properties that can be obtained by heat treatment. Earlier it was mentioned that iron can exist in two forms of space lattice: body-centered cubic at temperatures up to 910 C and face-centered cubic from 910 C to 1400 C. The temperature at which iron changes from the body-centered cubic to face-centered cubic is affected by alloying additions. The presence of 0.83 per cent carbon causes this phase change to occur at 723 C instead of 910 C (see Fig. 2.11).

Carbon is soluble in the face-centered cubic iron up to 1.7 per cent at 1130 C, but in the body-centered cubic iron it is soluble only to the extent of 0.08 per cent carbon at 723 C (see lines S-E and Q-P, Fig. 2.11). It is this difference in carbon solubility which gives steels their great range of properties on heat treatment. Austenite (a solid solution of carbon in  $\gamma$ -iron) transforms to ferrite (a solid solution of a tiny bit of carbon in  $\alpha$ -iron) and iron carbide upon cooling. By adjusting cooling rates, the dispersion of the iron carbide phase and hence the physical properties can be controlled.

Very slow or furnace cooling of steel produces *coarse pearlite*, which is composed of thick alternate plates of cementite and ferrite. The amount of coarse pearlite depends on the carbon content. If the steel has less than the eutectoid percentage of carbon, it is known as *hypo-eutectoid* steel, and the structure will consist of a mixture of pearlite and ferrite. If the steel contains more than the eutectoid percentage of carbon, it is known as *hyper-eutectoid* steel, and in it the excess cementite will tend to form a network around the pearlitic areas. The structure of the hypo-eutectoid steels, especially those having 0.5 per cent carbon or less, is relatively soft and ductile. That of the hyper-eutectoid steels is stronger and less ductile, but is still soft and ductile as compared to the same composition cooled at a much greater rate.

Air cooling a plain carbon steel from the austenitic condition gives *fine pearlitic* structure. In the pearlitic areas, the layers of ferrite and cementite are much finer than with furnace cooling and may measure as little as  $0.5 \times 10^{-6}$  in. thick. In this condition, the hardness and strength are improved while the ductility is slightly lowered.

Water quenching (very fast cooling) a plain carbon steel from the austenitic condition tends to retain all carbon in supersaturated solution in the  $\alpha$ -iron. The excess carbon atoms (over 0.08 per cent) strain the atomic arrangement to such an extent that a tetragonal lattice forms, intermediate to the  $\gamma$  and  $\alpha$  cubic types. The resulting structure which is known as *martensite* appears acicular or needlelike when viewed under the microscope. Martensite is very hard, strong, and brittle.

The reheating of the hardened steel is commonly called *drawing*, *tempering*, or *drawing back*. This operation softens the martensite by first causing actual formation of the carbide particles from carbon held in supersaturated solid solution, and then by causing growth of these carbide particles and of  $\alpha$ -iron grains having a normal  $\alpha$  lattice. As the tempering temperature is raised, the degree of grain growth of these phases increases continuously, resulting in structures having less hardness but more ductility than the martensite. Over a range of temperature from 200 C to about 500 C, the structure known as *troostite* is formed. It consists of submicroscopic particles of carbide in ferrite. At higher tempering temperatures, it changes by indistinguishable

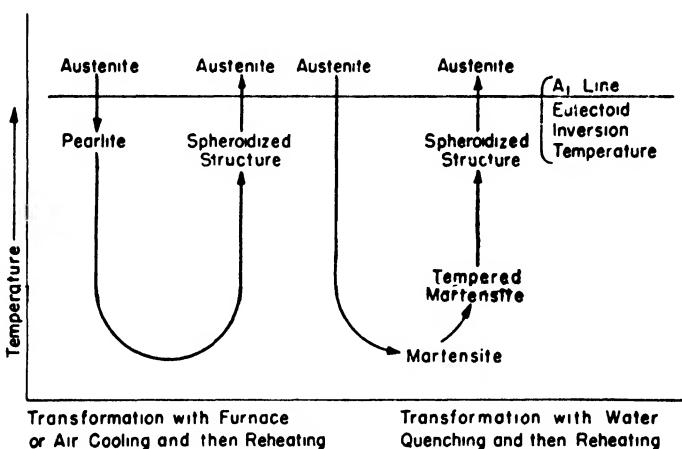


FIG. 2.12. Qualitative picture of the reactions in a plain carbon steel of eutectoid composition (0.83 C). (Time factor not shown.)

degrees into *sorbite*, in which the carbides have grown until the structure has a distinctly granular appearance. Although the names troostite and sorbite are frequently used, it is better to describe these structures as tempered martensite of a measured hardness. The spheroidized structure is the final stage of agglomeration where the carbide particles have grown to such an extent as to be actually visible under the microscope as spheroids of carbide in a matrix of ferrite. The hardness and strength of these temper products of martensite decrease with continued agglomeration of the carbide particles until this spheroidized structure is obtained. At that point, the steel is relatively soft and ductile.

The manner of producing these structures<sup>1</sup> in a eutectoid steel can be represented graphically as shown on Fig. 2.12. When *eutectoid*

<sup>1</sup> For photomicrographs of the structures discussed, see Chapter VI.

austenite is cooled relatively slowly in a furnace or by normal free convection in air, the structure changes directly to 100 per cent pearlite, and reheating for a rather long time just below  $A_1$  causes the iron carbide to agglomerate and produce the spheroidized structure. If the cooling is done quickly by quenching in water, the martensitic structure is obtained. Reheating this structure at successively higher temperatures from 200 C to 650 C causes the continuously merging degrees of precipitation and agglomeration termed temper troostite, sorbite, and finally the spheroidized structure.

In general, with uninterrupted rates of cooling of plain carbon steels, it is possible to produce only two structures, pearlite or martensite, or a mixture thereof. By no mechanism can pearlite transform into martensite or martensite into pearlite without first reheating to obtain austenite solid solution.

*Typical Reactions on the Iron-Carbon Diagram.* (1) 0.35 Per Cent Carbon Steel. This steel is typical of that used for forgings and structural members.

Above the  $A_3$  point at 790 C (Fig. 2.11), the steel exists as austenite or  $\gamma$ -iron with  $Fe_3C$  in solid solution. Upon slow cooling below this temperature, primary ferrite<sup>1</sup> begins to separate, making the remaining austenite richer in carbon. This continues until, at 723 C, the *remaining* austenite has eutectoid composition (0.83 per cent carbon) and transforms entirely into pearlite. The resulting structure is a mixture of grains of ferrite and areas of pearlite, and no further changes take place as the steel cools to room temperature.

(2) 0.83 Per Cent Eutectoid Carbon Steel. Above 723 C the eutectoid composition alloy exists as austenite. As the eutectoid temperature is passed upon cooling, *all* the austenite is changed to pearlite. There is no further change upon further cooling.

(3) 1.3 Per Cent Carbon Steel. High carbon steel such as this is used for cutting tools.

Above  $A_{cm}$  (line S-E on Fig. 2.11) at 1050 C, this steel also exists as austenite. Cooling causes primary cementite to separate, usually in the grain boundaries, thereby making the remaining austenite lower in carbon. This continues until, at 723 C, the *remaining* austenite is of eutectoid composition and additional cooling transforms it into pearlite. No further change takes place upon cooling to room temperature. The resulting structure is a network of cementite surrounding areas of pearlite.

Higher amounts of carbon in iron cause the eutectic composition at

<sup>1</sup> The term "primary ferrite" is used to distinguish this solid solution from the ferrite in the eutectoid grains of pearlite.

about 4.3 per cent carbon, known as *ledeburite*, to appear in the alloys which are slowly cooled. Except for the cast irons, there is little use for these alloys. The cast irons consist of many varieties, and in order to give them sufficient emphasis, they will be discussed in Chapter IV.

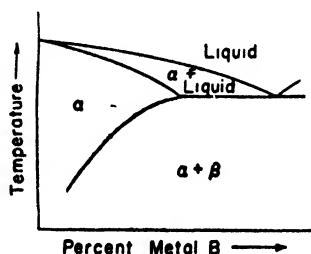
**2.8. Discussion.** This chapter has considered the formation and properties of alloys. Most binary alloys do not have constitution diagrams of the pure types described, but instead their diagrams are a combination of these and other types. Frequently the combination is quite complicated. The advantage of discussing the characteristic systems lies in straightforward explanation of fundamental phenomena and in the facility of extending associated characteristics to the actual alloys by comparison of constitution diagrams.

Because of the extremely large number of possible alloy combinations, the discussion is limited to the simple two-element or binary systems. The effect of not maintaining equilibrium conditions is pointed out by illustrating hardening by precipitation and by the heat treatment of steel.

Additional alloying elements will affect the properties of the binary systems discussed. The effect depends upon the manner in which the new elements alloy themselves with the elements already present. Few general rules for predicting properties seem to apply, but much experimentation has furnished a lot of empirical data on the more important engineering alloys. Those which are of industrial importance, particularly to the electrical industry, will be discussed in succeeding chapters.

### REVIEW QUESTIONS

1. What is an alloy?
2. How may the alloying elements arrange themselves with the base metal in an alloy?
3. Explain the difference between a eutectic point and a eutectoid point.
4. Why is it desirable to avoid a eutectic composition when choosing a solder for "wiping" a joint?
5. What is coring, why is it objectionable, and how is it eliminated?
6. By means of the sketch shown, describe precipitation hardening.
7. What is the purpose of heat treatment?
8. What are the following and how are they obtained? Ferrite, austenite, cementite, pearlite, martensite, ledeburite.



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## CHAPTER III

### MECHANICAL PROPERTIES OF METALS

By J. F. YOUNG and J. B. LAMBERT

**3.1. Introduction.** Those properties which define the behavior of a material under applied forces or loads are broadly classed as *mechanical properties*. They are a measure of the strength and the endurance of a material in service, and are of great importance to the designer, who must provide adequate life and performance in machines and structures. The following discussion will be limited to these mechanical properties, although in a particular design other properties such as color, texture, appearance, electrical conductivity, galvanic action, and heat conductivity may also be of importance.

The real criterion of the suitability of a material is that it shall give the desired performance when in service. Sometimes the properties required for such performance can be evaluated only by observing the part in actual use and by estimating the degree to which these properties are present. Unfortunately, this estimate can be only qualitative, i.e., it indicates only whether the material is too good, satisfactory, or too poor. The choice of a material for new applications of this type must therefore be based upon the designer's experience. When the application is completely unfamiliar to him, it may be necessary to build development models to establish the fitness of the materials or the design.

For many other applications, the properties needed in the material can be evaluated quantitatively by standardized laboratory tests on sample specimens. The properties measured in this way are those normally thought of as the mechanical properties. They may be of two types:

- (a) Properties of an *absolute* nature, which are used directly in design calculations.
- (b) Properties of a *relative* nature, which are not useful in design calculations but which establish a material as similar in quality to another found by experience to be satisfactory in service.

Successful interpretation of the test results requires an understanding of the effects of many different variables, such as form and size of the

part, service conditions (temperature, corrosion, etc.), and method of loading. There are many ways in which test loads may be applied, but for the purpose of discussion, they will be arbitrarily divided into three classes: *static*, *cyclic*, and *impact*.

*Static* loads are assumed to include all loads that are applied slowly enough so equilibrium of forces is essentially maintained.

*Cyclic* loads are those that are applied and wholly or partly removed or reversed enough times to cause the material to behave differently than when under static load. When this effect occurs, the material is said to be subject to *fatigue*.

*Impact* loads are loads of such a nature that the material must absorb a definite amount of energy instead of resisting a definite force as in static and cyclic loading.

Each of the tests normally performed in the laboratory as a measure of mechanical properties will be discussed under one of these classes of loading. Specific reference will be made only to pure metals and alloys, but a number of the properties discussed will, of course, apply to non-metallic materials also.

### STATIC LOADS

Many properties of a metal<sup>1</sup> are determined by slowly applying a load to a suitable specimen and observing the amount that it deforms. The temperature at which such a test is conducted has a great effect on the behavior of the specimen, so property tests at normal (room) temperature and at abnormal (above or below room) temperature will be considered in separate sections. When the duration of loading also has a significant effect, it will be mentioned.

#### STATIC LOADS AT NORMAL TEMPERATURES

**3.2. Stress and Strain.** When a static load is applied to a machine part or assembly, that load produces reaction forces throughout the part, and it is by means of these forces that the load is transmitted through the part to the supports. The intensity of the reaction force at any point in the part is called the *stress*. Sometimes it is helpful to visualize the stress as the force per unit area exerted by the material on one side of an imaginary plane of separation in the part upon the material on the other side. When the forces are parallel to the imaginary plane at the point, the stress is called *shear stress*; for forces perpendicular to

<sup>1</sup> The term *metal*, in the scientific sense, means only pure metals and does not cover alloys. In a commercial sense, however, it means both pure metals and alloys. In this chapter the term will be assumed to have the latter meaning.

the plane the stress is called *compressive stress* or *tensile stress*, depending on whether it tends to bring the material in closer contact or to separate it. Stress and unit stress are used interchangeably to mean force per unit area, and are usually expressed in pounds per square inch.

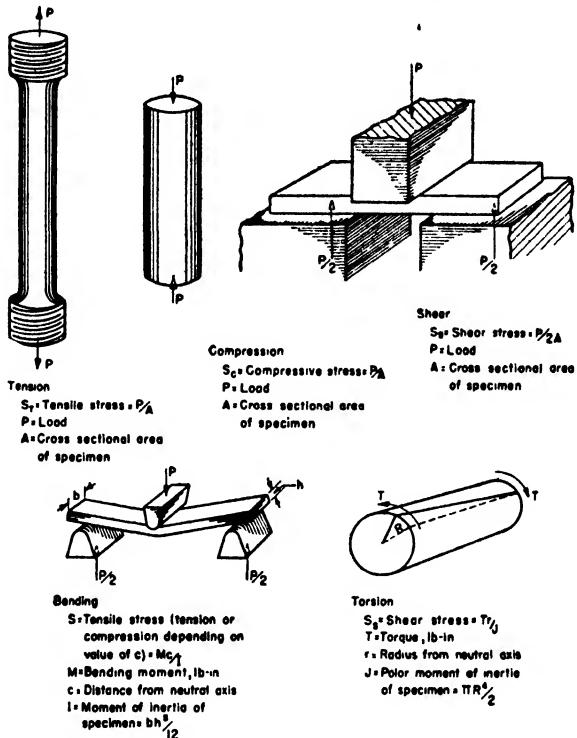


FIG. 3.1. Sketches of the common test specimens. The stress distribution in each is given by the accompanying equations.

To test the behavior of materials under each of these types of stress, sample specimens are chosen of such shape that the distribution of the reaction forces, and therefore the stress, is known. Fig. 3.1 shows sketches of some of the common test specimens. In the tension, compression, and shear tests, the stress is assumed to be uniformly distributed over the cross-section perpendicular to the load. The stress in the bending and torsion tests is not uniformly distributed, but its variation can be predicted from the theory of elasticity and is given by the expressions on the figure.

When a part is loaded, and supports stress, it is deformed or strained from its original unstrained dimensions. The amount of strain in any direction depends upon the magnitude and duration of the stress, and

upon the condition of the material. *Strain* and *unit strain* are used synonymously to indicate the deformation per unit length. They are measured in a dimensionless unit such as inches per inch, or in percentage. The strains resulting from the loads applied to the test specimens mentioned above are shown in Fig. 3.2. Strain produced by uniaxial tension is known as *elongation*.

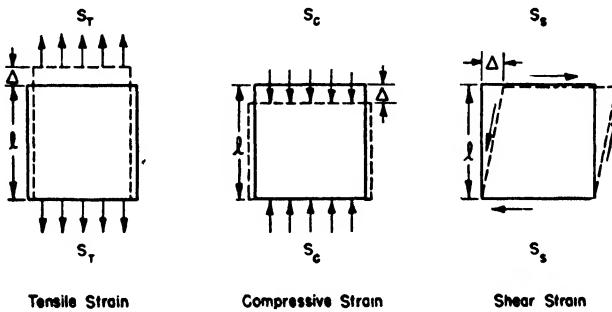


FIG. 3.2. Strains resulting from three types of stress.

**3.3. Strength.** In the common static load tests, a gradually increasing load is applied to the specimen and the strain in the direction of loading is periodically measured until failure occurs. The stress is

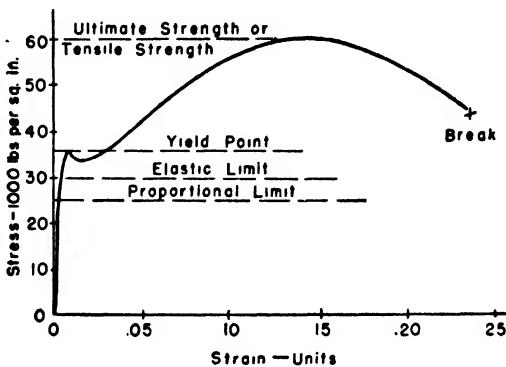


FIG. 3.3. Stress-strain curve for 0.30 carbon steel loaded in tension. Mild steels and wrought iron have this type of curve.

calculated from the loads and the original dimensions of the specimen, and this stress is plotted graphically with respect to its corresponding strain. The resulting graph is called a stress-strain curve. Tensile stress-strain curves for two different metals are illustrated in Figs. 3.3 and 3.4. Fig. 3.5 illustrates both tensile and compressive stress-strain

curves. These tests are referred to as *short-time* tests because the period of loading normally does not exceed one-half hour.

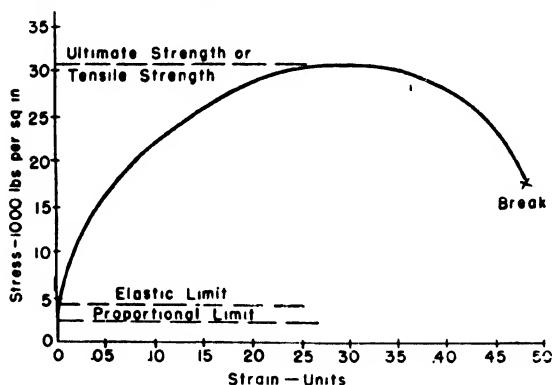


FIG. 3.4. Stress-strain curve for annealed copper loaded in tension.

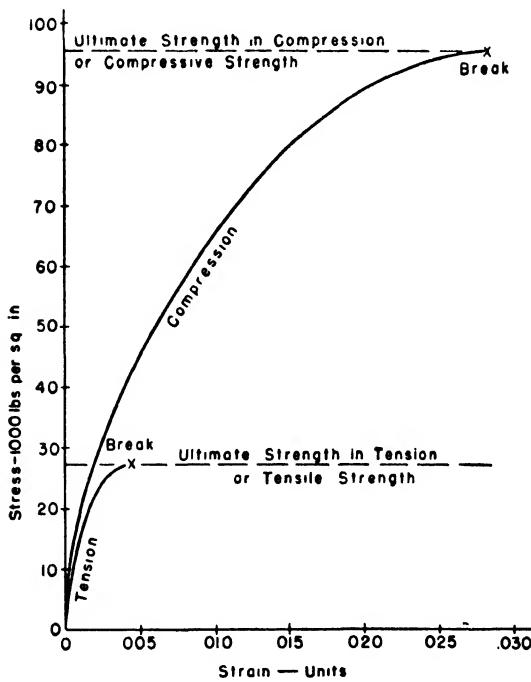


FIG. 3.5. Stress-strain curve for cast iron loaded in tension and compression.

The fracture or break in a tension test is usually accompanied by a "necking down" or reduction in cross-sectional area of the test bar at the point where the fracture occurs. Since the load applied produces

stress which is distributed over this reduced cross-section, the maximum stress supported should be calculated from the load and the area of the minimum cross-section. It is customary, however, to use the original dimensions when calculating stress because of the difficulty and danger to equipment of continually remeasuring the actual area during test. This method of calculating the stress accounts for the droop in the tensile stress-strain curves, Figs. 3.3 and 3.4, for the actual stress required to cause failure increases to the point of fracture. The stresses for other tests are also calculated on the original dimensions, causing similar differences between the actual stress and the stress plotted on stress-strain curves.

Stress-strain curves' are a measure of the strength of a material — the capacity of the material to support a load. The various strength properties taken from these curves are as follows.

*Proportional Limit.* As long as the stress-strain curve is straight from the zero point (origin), strain is proportional to stress and *Hooke's law* of proportionality between strain and stress applies. Above some value of stress, the ratio of stress to strain is no longer constant and the curve will bend to the right. The value of stress at which this change first occurs is termed the *proportional limit*. The proportional limit is high for steels and low for cast iron and ductile materials such as copper and aluminum (see Figs. 3.3, 3.4, and 3.5).

*Elastic Limit.* The *elastic limit* is the maximum stress which can be applied to a metal without causing a plastic deformation which will remain after the load is relaxed to zero. The stress-strain curve does not show the elastic limit; it can only be found by successively loading and unloading the test specimen. Normally for ductile metals the elastic limit is slightly above the proportional limit.

As the sensitivity of strain-measuring devices has been improved, successively lower values of elastic limit have been found for most metals. It is therefore possible that metals actually have no true elasticity during the first loading cycle. For practical purposes, however, the elastic limit based on observable permanent deformation in the usual testing procedure is a useful concept, particularly since strain hardening results in an increased elastic range for load applications subsequent to the first one.

*Permanent Set.* When a metal remains deformed from its original dimensions after forces applied to it have been reduced to zero, it is said to have undergone plastic deformation, and the amount of deformation is called the *permanent set*.

*Yield Point.* At a certain stress called the *yield point*, low-carbon and annealed medium steels begin to slip rapidly along atomic planes

and a relatively large deformation takes place with no increase (sometimes with a decrease) in load. This point is indicated by a slight reversed curve or "knee" in the stress-strain curve (see Fig. 3.3).

**Yield Strength.** Hard steels, soft metals such as copper, and brittle materials such as cast iron show no yield point or "knee." To assign to these metals some measure of their deformation, the property called

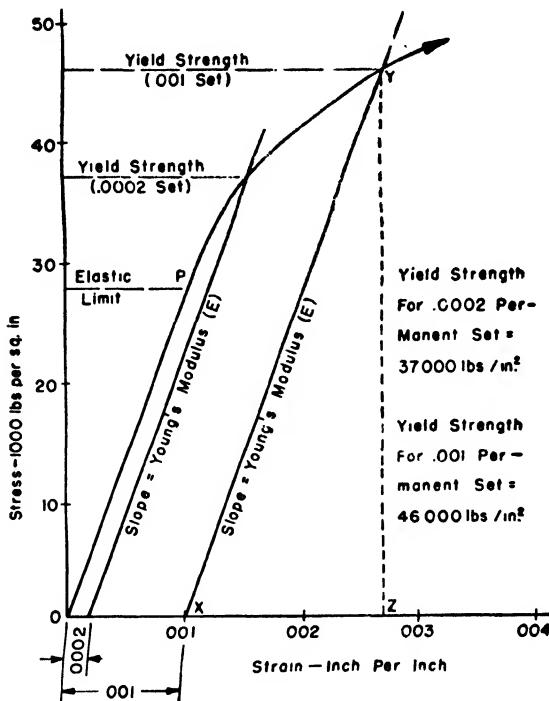


FIG. 3.6. Lower portion of the stress-strain curve for stainless steel (18-8). The "offset" method for determining yield strength is indicated.

*yield strength* (sometimes *proof stress*) is used. A permissible permanent set is chosen, and the stress which will cause this value of set is defined as the yield strength. The significance of yield strength may be seen from Fig. 3.6, in which  $OPY$  is the stress-strain curve. If the metal is stressed to a point  $Y$  on the curve and then the load is removed slowly, the stress-strain characteristic will follow the line  $YX$ , which is very nearly parallel to  $OP$ . When the stress is zero, the metal will have recovered elastically by an amount  $ZX$ , but will retain a permanent set  $OX$ . Stress  $ZY$  is therefore the yield strength of the metal at set  $OX$ . When the stress-strain curve is available, the yield strength may be

determined by the "offset method." The permissible set, for example  $OX$ , is laid off on the strain axis, and a line drawn through  $X$  parallel to  $OP$ . The line will intersect the curve at some point  $Y$ , and  $ZY$  is the yield strength. It should be noted that a numerical value for yield strength has no significance unless the permanent set is specified. It has become standard practice to use the 0.5, 0.75, or 1 per cent (0.01 strain) yield strengths for certain copper base alloys, and 0.2 per cent yield strength for aluminum and magnesium base alloys.

*Ultimate Strength.* After the mild steel has undergone its plastic deformation at the yield point, it is capable of supporting more load (Fig. 3.3) because of the strain-hardening effect mentioned in Chapter I. The maximum stress which any metal will withstand is called its *ultimate strength* or commonly its *tensile strength*, *compressive strength*, or *shear strength*, depending on which type of stress is established. The ultimate strength is the highest stress which the stress-strain curve reaches. It is the stress at rupture for metals such as cast iron (Fig. 3.5) but is *not* the stress at rupture for metals such as soft steel and copper (Figs. 3.3 and 3.4), in which the stress-strain curve has a droop preceding rupture.

*Modulus of Rupture.* The *modulus of rupture* is a fictitious stress calculated for either bending or torsion tests on the basis of the load causing failure, and the assumption that the elastic equation for stress applies up to the point of failure. In the bending test, the bending moment  $M$  at failure is substituted in the flexure equation,  $S = Mc/I$  (see Fig. 3.1), and the tensile or compressive stress calculated for the extreme fibers of the beam is the modulus of rupture. Similarly for torsion, the modulus is the fictitious shear stress at the surface of a cylinder computed from  $S_s = Tr/J$ , where  $T$  is the twisting moment that causes rupture.

**3.4. Stiffness.** The resistance of a metal to elastic deformation is called its *stiffness*, and is very often a limiting design factor. For example, bridges are usually heavier than would be required to support traffic and this heaviness is to prevent swaying and sagging of the bridge when in use. A jackknife blade is much thicker than would be required to prevent its being broken in ordinary service — the added thickness is to keep it from buckling or bending.

Peculiarly enough, the stiffness of a metal is varied very little by alloying with other elements. If a steel beam sags too much under load, nothing will be gained by changing to a stronger alloy steel. The strength will be increased, but if the load is the same, the beam will still sag about the same amount. The remedy is to increase the cross-section of the beam.

The stiffness of a metal is measured by the moduli of elasticity in tension, compression, and shear, by Poisson's ratio, and by the bulk modulus of elasticity.

*Modulus of Elasticity in Tension and Compression.* The *modulus of elasticity* is a measure of the perfectly elastic deformation of a metal when stressed in tension or compression within the proportional limit. Its value is equal to the ratio of stress to strain, and corresponds to the slope of the stress-strain curve. Referring to Fig. 3.2, the modulus of elasticity, also called *Young's modulus*, is

$$E = \frac{S_t}{\Delta/l} \quad \text{or} \quad E = \frac{S_c}{\Delta/l}$$

where  $S_t$  and  $S_c$  are the tensile and compressive stress, and  $\Delta/l$  is the strain caused by each stress. Because strain is a dimensionless quantity, the Young's modulus,  $E$ , has the same dimensions as stress, usually pounds per square inch.

Young's modulus for steels at room temperature, regardless of treatment, alloying, or metallurgy, is between 27 and 30 million lb per sq in. For all gray cast iron it is between 14 and 18; for copper and its alloys, about 14; and for all aluminums, about 10 million. (See Table 3.1 at end of chapter.)

*Modulus of Elasticity in Shear.* This number is of the same nature as Young's modulus except that it refers to the ratio of *shearing stress* to *shearing strain*. It is also known as the *modulus of rigidity* or *shear modulus* and is denoted by  $G$ . Referring to Fig. 3.2, its value is

$$G = \frac{S_s}{\Delta/l}$$

where  $S_s$  is the shearing stress and  $\Delta/l$  is the strain caused by  $S_s$ . For homogeneous, resilient materials (capable of storing elastic energy),  $G$  is equal to  $0.4E$  and most metals have a relationship very near to this. Values of  $G$  are also given in Table 3.1.

*Poisson's Ratio.* When a metal is subjected to a longitudinal tensile stress, it will elongate, and in an attempt to retain its original volume, will also decrease in cross-section. If the stress were compressive, longitudinal shortening would be accompanied by an increase in the cross-section. The ratio of the strain in a lateral direction to the longitudinal strain under the conditions of uniform and uniaxial stress within the proportional limit is known as *Poisson's ratio*. It is denoted by  $\sigma$  (sigma), although sometimes the symbols  $\mu$  (mu) or  $1/m$  are

used. Poisson's ratio is related to the other moduli by the equation

$$\sigma = \frac{E}{2G} - 1$$

and is between 0.25 and 0.33 for most metals. If the volume remained constant,  $\sigma$  would be 0.50; therefore the volume of most metals increases slightly when loaded in uniaxial tension and decreases when loaded in uniaxial compression.

*Bulk Modulus of Elasticity.* This modulus is the ratio of a uniform, triaxial (equal in all directions) tensile or compressive stress to the relative change in volume it produces. It is not of particular importance because this type of loading is seldom encountered.

**3.5. Resilience.** The elastic energy stored in a unit volume of a material, as a result of applied loads, is its *resilience* and is expressed in energy units such as foot-pounds per cubic inch. The maximum amount of elastic energy that may be stored in the material during its first loading cycle is called its *proof resilience*. It is determined at the elastic limit of the material. In Fig. 3.16, curve *OEYA* represents the first part of the stress-strain diagram for a low-carbon steel. The area *OES* under this curve is equal to the proof resilience of the steel. The proof resilience of copper is very small, as shown in Fig. 3.17, because the elastic limit is so low that copper is almost incapable of storing elastic energy. The resilience of different metals is often compared by bouncing a hard steel ball on each and noting the relative height of the rebounds — the more resilient metal will cause the higher bounce. The Schore scleroscope embodies this method of testing.

**3.6. Toughness.** The work per unit volume required to fracture a metal is called its toughness, and is equal to the total area under the stress-strain curve. It is a measure of the total energy-absorbing capacity of the metal and includes both elastic and plastic deformation. Some mild steels are tougher than hard steels because the plastic deformation at fracture for the latter may be quite small. Toughness shows some relationship to impact strength, i.e., resistance to shock loads, but the energy values measured in a static test and an impact test do not agree for all metals or test conditions.

**3.7. Ductility, Malleability, and Brittleness.** A metal which may be worked to a different size or shape without breaking or shattering is *ductile* or *malleable*, but if only a very small change in dimensions can be made before the metal fractures, it is *brittle*. The arbitrary dividing line between brittleness and ductility is usually placed at 5 per cent tensile strain (elongation) of a 2-in. test bar at rupture, brittle materials having less and ductile materials having more than this elongation.

Metallurgists sometimes distinguish between brittleness and ductility by the appearance of the fracture. Fractures which follow the grain boundaries are called brittle fractures, and those which occur through the grains themselves are called ductile fractures.

Although the terms ductility and malleability are frequently used interchangeably, the *ductility* is more often thought of as a tensile quality, the ability of the metal to be drawn out or stretched, whereas *malleability* is considered as a compressive quality, the ability of the metal to be beaten out or flattened. These qualities are of great importance in a metal which is to be worked to its finished form.

**3.8. Hardness.** The hardness of metal is difficult to define as a distinct property because it is closely associated with the structure the composition, and the other mechanical properties. Consequently, a number of different kinds of hardness have come to be recognized. Each arises from tests devised to measure the effect of hardness on the usefulness of a metal in actual service. For convenience, those tests which measure indentation hardness will be considered here, and those indicating resistance to abrasion, wear, cutting and dynamic indentation (penetration) will be considered later.

Indentation hardness is most commonly tested by the Brinell, Rockwell, Vickers, and Monotron tests.

*Brinell Hardness Test.* In this test, a standard load (3000 or 500 kg) is applied to a smooth surface of the metal through a hardened steel ball (one cm diameter). The diameter of the resulting spherical impression is measured and from it the *surface area* of the indentation is calculated. The numerical value of Brinell hardness is equal to the load divided by this area: Brinell hardness number (*Bhn*) = load/area.

There are several limitations to the standard tests: (a) They cannot be used for very hard or very soft metals. For metal harder than about 500 Brinell number, special tests employing a Carboloy or diamond ball are available; special light loads are used for testing very soft metals. (b) The indentation should not mark through the specimen, so the minimum thickness of steel that can be tested is about 0.1 in. (c) The test must be made far enough from the edge of the metal so no bulge results. (d) The edge of the indentation is not always distinct.

Frequently in production-control work, the Brinell number is calculated from the depth of indentation because depth is easier to measure than diameter. This method is not recognized as standard, however.

*Rockwell Hardness Test.* In the Rockwell tests, a standard minor load is applied to seat the indentor in the surface of the metal before a standard major load is applied. The indentor used may be a hardened steel ball, or a diamond cone, called a *brale*, which has a spherical apex.

Choice of the indentor, as well as the major load applied, depends on the hardness of the metal to be tested. The combination should result in a nearly mid-scale indication on the scale provided. This scale is arbitrarily calibrated to indicate hardness numbers for the depth of indentation caused by the major load alone. The numbers increase with hardness. Naturally, different indentors and loads result in different hardness readings so a letter is included with the reading to indicate the combination used, e.g., Rockwell B 100. The Rockwell B (1/16 in. diameter ball and 100 kg load) and Rockwell C (brale and 150 kg load) tests are used most frequently for structural steels and hard steels respectively.

A special test known as the *Rockwell superficial hardness* test is used where a very shallow impression over a very small area is desired. It employs lighter minor and major loads with either type of indentor, and a more sensitive depth measuring system. It is used for thin strip or sheet, nitrided or lightly carburized parts, finished pieces on which test marks are undesirable, areas near edges, very small parts or sections, and shapes that would collapse under the heavier loads.

*Vickers Hardness Test.* The Vickers test resembles the Brinell test, but instead of a hardened steel ball, it employs a small diamond in the shape of a square-based pyramid (136 deg.). Various loads are used according to hardness and thickness of the part. The hardness number is represented as the ratio of load to the surface area of the indentation.

*Monotron Hardness Test.* The Monotron tests register the load that must be applied to a hardened ball to produce an indentation of fixed depth. The standard indentors read directly in Brinell numbers and may be used for most all steels, with or without prepared surfaces.

*Comparison of Various Hardness Tests.* The hardness numbers for several structural steels tested by the above methods are given for comparison in Table 3.2. Curiously enough, for carbon and low alloy steels the Bhn multiplied by 500 is approximately equal to the tensile strength, but such a relation does not hold for highly alloyed steels, case hardened steels, or nonferrous metals. These hardness tests are most useful for establishing the quality of a metal, rather than to provide quantitative design data.

**3.9. Discussion.** A few general observations with regard to room temperature stress-resistance of metals are mentioned in the following paragraphs.

(1) The compressive stress-strain curve for mild steel shows a knee similar to that in the tensile curve. Young's modulus is the same for both tension and compression, but the values of elastic limit and yield point in compression are about 110 or 115 per cent of their values in tension.

TABLE 3.2. APPROXIMATE COMPARISON OF HARDNESS NUMBERS, RESILIENCE NUMBERS, AND TENSILE STRENGTHS FOR STRUCTURAL STEELS

Hardness				Tensile Strengths	Resilience
Rockwell C Scale No.	Rockwell B Scale No.	Vickers Firth Diamond No.	Brinell 3000 kg No.	Standard Test lb./sq.in	Schore Scleroscope No.
59	...	715	600	300,000	81
51	118	546	500	250,000	68
42	113	418	400	200,000	55
32	107	302	300	150,000	43
14	93	200	200	100,000	29
..	55	100	100	50,000	..

(2) Data on stress-strain characteristics in shear are difficult to find but may be estimated from other available data. The modulus of rigidity for metals is about 40 per cent of Young's modulus, and the ultimate strength in shear expressed as a percentage of tensile ultimate strength is roughly as follows:

Material	$\frac{\text{Ult. shear strength}}{\text{Ult. tensile strength}} \times 100$
Aluminum	60%
Steel	75
Copper	90
Malleable Iron	90
Cast Iron	130

(3) Increasing the carbon content of steel increases its strength and decreases its elongation at fracture, as shown in Fig. 3.7.

(4) The stress-strain curves for three ductile materials are compared in Fig. 3.8. Note that no fracture accompanies the compression tests because the ductility of the materials permits continued deformation of the original test cylinders until they are flattened into plates.

(5) Annealing has the effect of decreasing strength and increasing ductility (Fig. 3.9).

(6) In most metals, the proportional limit and the elastic limit are so close together that they are considered as having the same value. Cast iron, however, is the outstanding example of a metal which has an elastic limit much larger than its proportional limit, in fact, very near to its ultimate strength. This explains why cast iron cannot be given

an appreciable permanent set, and its fracture in tension shows very little reduction in area.

(7) The stress-resistant properties of steel, copper, aluminum, and

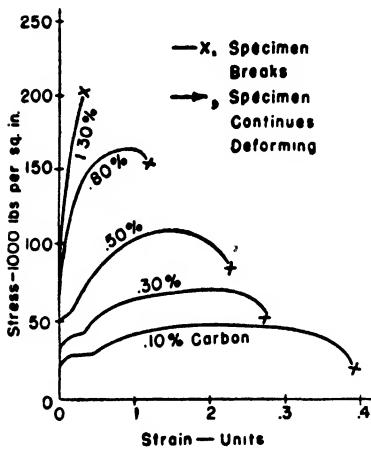


FIG. 3.7. Effect of carbon content on the strength of annealed steel in tension.

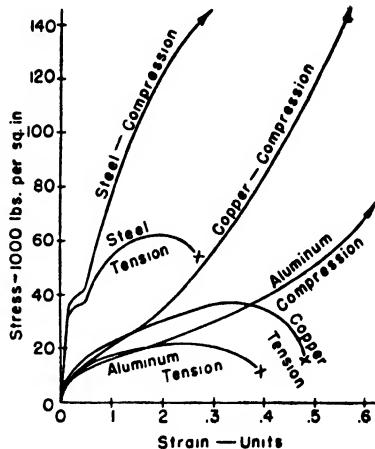


FIG. 3.8. Comparisons of ductile metals in tension and compression.

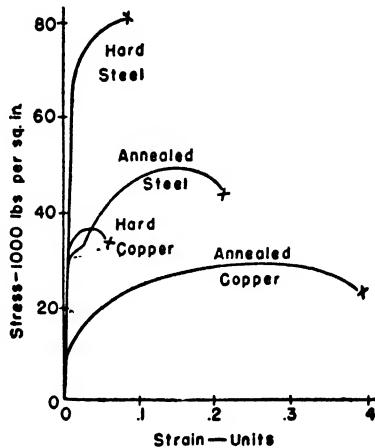


FIG. 3.9. Effect of annealing on the strength of cold worked copper and medium carbon steel.

most other metals are greatly increased by cold working such as rolling and drawing. These operations have little effect on lead because it recrystallizes at room temperature.

(8) The tests considered thus far have been for short-time static loading. A load may be applied for a long period of time (several years) without causing an appreciable reduction in strength, providing the temperature remains below the recrystallization temperature of the metal. (See Sec. 3.11.)

(9) The ratio of the yield-point stress to the tensile strength is referred to as the *elastic ratio*. It ranges from 50 to 65 per cent for low carbon steels, and may be raised to 75 per cent and above by cold working, or by the addition of certain alloying elements and proper heat treatment.

(10) Tests upon single crystals of metal show that the properties vary with the direction of loading. In iron, for instance, the modulus of elasticity for three different planes has been determined as 19 million, 31.3 million, and 40.5 million lb per sq in. It is evident that for the modulus of elasticity and other properties to be equal for several pieces of the same material tested in random directions, the grains must be of random orientation, and of small size relative to the size of the part. When this is the case, the material is essentially isotropic (equal properties in all directions).

The natural tendency for the location, size, and orientation of the grains to follow a statistical distribution makes the properties themselves statistical in nature. That is, they show some variation due to chance causes. It should therefore be recognized that the property values reported in the literature may be slightly higher or lower than the properties of other pieces of the same material given the same treatments and tested in the same way.

Some of the effects of grain size on strength will be discussed in Chapter VI.

(11) If a metal part supports a combination of two or more types of stress, the magnitude of the maximum stress at failure may not be the same as if the part were in simple tension, compression, or shear. The effect of such combined stresses seems to vary with different materials and to a lesser extent with the types combined. The present trend, particularly in aircraft design, toward using structural materials closer to the limit of their strength and in more complicated members which may support many loads makes this effect of considerable importance. Industry has begun to test materials under the action of combined stresses. Several static loading devices for applying compression, tension, and torsion simultaneously in various combinations are available. The effect of mutually perpendicular tensions is tested by rotating thin disks at steady speed. It is expected that this phase of mechanical testing will be greatly expanded during the next few years.

### STATIC LOADS AT ABNORMAL TEMPERATURES

**3.10. Short-Time Static Loads.** Many types of structures and apparatus are subjected to loads while at relatively low or high temperatures. The effect of these temperatures on the short-time static test properties of metals will be considered in this section.

*Low Temperatures.* Low temperatures are encountered in equipment for refrigeration, for some manufacturing processes, for arctic climates, and for aircraft which operate at high altitudes. Most of these applications are of comparatively recent development, or of only limited interest; consequently the metal properties at low temperature have not been studied extensively.

The relative absence of metallurgical changes in most metals with decreasing temperatures suggests that abrupt changes in the properties as the temperature is lowered are not to be expected. Those tests<sup>1</sup>

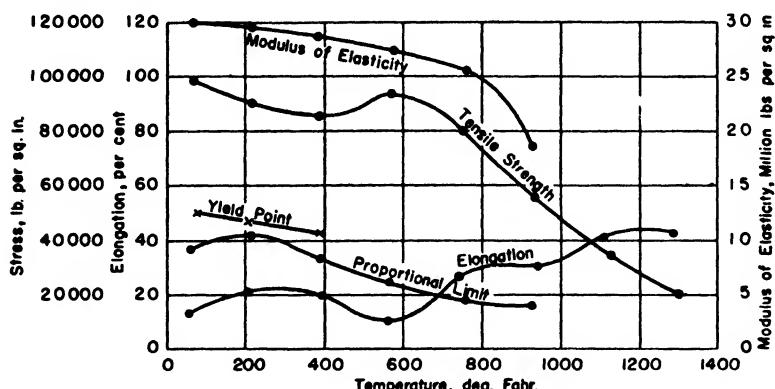


FIG. 3.10. Effect of temperature on the short-time static strength of 0.53 per cent carbon steel. From tests by H. J. Tapsell and W. J. Clenshaw, "Properties of Metals at High Temperatures II," Engineering Special Report No. 2, Dept. of Scientific and Industrial Research, Great Britain, Sept. 1927.

which have been conducted show this to be the case. In general, metals show a continuous increase in yield strength, tensile strength, hardness, and modulus of elasticity and a small decrease in tensile elongation. To develop these properties, particularly in the hardening alloys, proper heat treatment must be used.

Low temperatures also usually cause an increase in endurance limit and a decrease in impact resistance. These two properties will be dis-

<sup>1</sup> For example, see H. W. Russell, Battelle Memorial Institute, "Effect of Low Temperatures on Metals and Alloys," article in symposium on "Effect of Temperatures on Metals," A. S. T. M. and A. S. M. E. pub., 1931.

cussed later, but it is noted that the decrease in impact resistance with decreasing temperature is particularly large in ferrous alloys in which the iron is in the form of ferrite.

*High Temperatures.* Numerous tests have been made on metals at high temperature because of the large number of applications (engines, turbines, boilers, furnaces, stills, etc.) which involve high-temperature service. When heated above room temperature, most metals undergo metallurgical changes with consequent changes in mechanical properties. Steel and other alloys exhibit these changes to a marked degree and as a consequence there are inflections and humps in their short-time strength-vs.-temperature curves (for example, see Fig. 3.10). The curves for all metals show that strength decreases greatly at elevated temperatures; so for extremely high temperatures ceramics are used instead of metals.

Stiffness decreases continuously as the temperature is increased, and drops off abruptly at the recrystallization temperature. (See Fig. 3.10.) At this and higher temperatures, the modulus of elasticity is difficult to interpret from the stress-strain curves.

**3.11. Creep at Elevated Temperatures.** In 1920 Lea and others published results of tests on ferrous metals subjected to constant loads for long periods of time at elevated temperatures. The specimens were found to deform continuously during test, even though the stresses were less than the apparent yield point for a short-time test on the metal at the same temperature. This phenomenon of continuous stretching under load is the phenomenon of *creep*. It occurs even when the metal is loaded at room temperature, but in steels the amount is not measurable nor of practical significance compared with that which occurs at elevated temperatures.

Although Lea's investigation of creep started extensive research in many countries, this study is still in its infancy and the data on the progressive failure of metals at high temperatures are as yet not very well correlated. The main trouble is that the factors which affect creep are so numerous and complexly interrelated that it is impossible to vary just *one* and study its effect. *What* alterations in structure are brought about by changing such variables as chemical composition, melting process, forming process, and heat treatment are quite generally known; but *which* of these alterations accounts for the change in creep resistance of the metal continues to be the basis for speculation by creep theorists. Many changes not attributable to the stress take place during the long period of heating, thus complicating the analysis. Of the numerous theories which have been advanced, only a few major concepts will be discussed.

**3.12. Theory of Creep.** If a creep test is conducted at high enough stress or temperature, or for a long enough time, the test specimen will fracture. Between the time the load is applied to the material and the time, perhaps years later, when the fracture occurs, the material appears to pass through three rather well defined stages of creep. These are illustrated in Fig. 3.11.

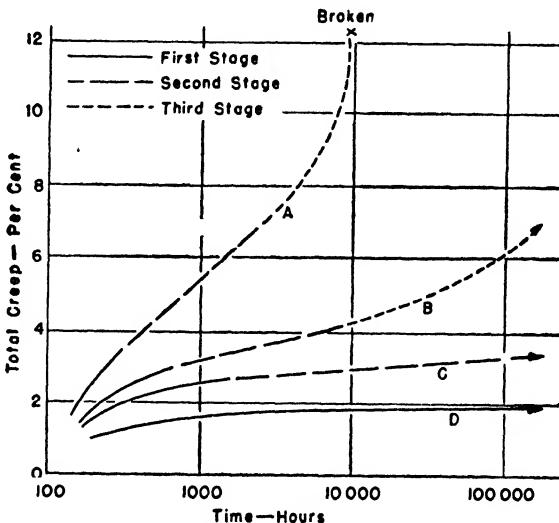


FIG. 3.11. Creep-vs.-time curves for a chrome-nickel steel. Curves A, B, C, and D represent successively lower temperatures for the same applied stress, or successively lower stresses for the same temperature.

(1) *First Stage — Stress Readjustment and Strain Hardening.* When the load is first applied, the stress does not distribute uniformly throughout the metal. Minute stress concentrations appear at all irregularities in structure, for example, at grain boundaries, and, in steel, at the boundaries between ferrite and cementite, which have different elastic properties. To relieve and distribute this stress, interatomic slippage will take place wherever it most easily can, and this slippage causes distortion of the crystal lattice. If slight thermal agitation causes re-alignment of the lattice, this is termed *crystal repair* or annealing. If the lattice remains distorted, however, further slippage is hindered and the metal is said to *strain harden*. After stress relief in the places most favorable to slip, slippage takes place with greater difficulty elsewhere, which accounts for the creep-vs.-time curve bending to the right (see Fig. 3.11, first stages of curves). This slippage gradually decreases stress concentrations and distributes the stress evenly throughout the metal. If the combination of stress and temperature is low

enough, first-stage creep may proceed throughout the entire service of a metal part (curve *D*, Fig. 3.11).

(2) *Second Stage—Strain Hardening and Annealing.* If the temperature is sufficiently high, annealing may, after a time, become as active as strain hardening, so that these two tendencies balance each other and creep proceeds at a constant rate. This is the second stage of creep and is indicated by the straight portions of the curves, Fig. 3.11. If annealing becomes predominant over strain hardening, creep will enter stage three.

(3) *Third Stage—Annealing and Necking.* As the annealing becomes more pronounced, the rate of creep increases and the metal may neck down and ultimately fracture.

**3.13. Creep Specifications.** It is often more important for a designer to know *how much* a part will creep rather than *how fast* it will creep, but *creep rate*, expressed in percentage elongation per hour (at a certain number of hours), is nevertheless the most common way in which the creep resistance of metals is indicated. This is often misleading and *total creep* expressed in per cent (at a given number of hours) may be of more importance where deformation must be limited. For example, the slope of curve *A*, Fig. 3.11, shows the creep rate at 1000 hr to be 1.55 per cent per 1000 hr. Nevertheless, in the first 1000 hr the total creep has actually been 5.4 per cent. It is advisable for the designer to consult data both on total creep and on creep rate when they are available.

**3.14. Constant-Load Creep Tests.** The usual method of performing a creep test is to maintain a standard test specimen at a constant temperature under a fixed load, and to observe the strain from time to time. Other specimens are tested similarly under different loads or at different temperatures, and the resulting data are summarized, for use in design, in the form of composite diagrams. Four of these diagrams are discussed below.

(1) *Creep-vs.-Time Diagrams.* If the data taken during the creep test are plotted directly, a creep-vs.-time diagram such as Fig. 3.11 will result. Each curve, *A*, *B*, *C*, and *D*, represents a different combination of stress and temperature for a chrome-nickel steel.

(2) *Creep-vs.-Stress Diagrams.* A diagram of this type may be obtained by cross-plotting from a creep-vs.-time curve. The total creep in a given period, for example 10,000 hr (14 mo), is plotted with respect to the stress which caused it (see Fig. 3.12).

(3) *Stress-vs.-Temperature Diagrams.* A stress-vs.-temperature diagram shows the stress which will cause a given total creep or a given creep rate (second stage slope) at a given temperature. Four such

curves for three steels are plotted in Fig. 3.13. Diagrams of this type are obtained by plotting from a number of creep-vs.-time diagrams for different stresses and temperatures.

(4) *Stress-vs.-Time Diagrams.* This type of diagram is obtained by cross-plotting from single-temperature creep-vs.-time diagrams. Curves

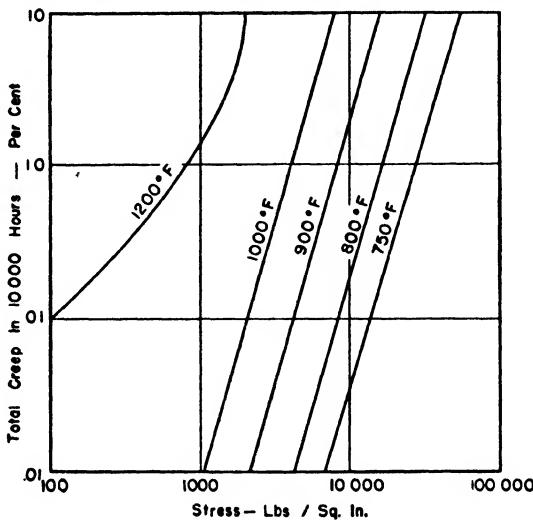


FIG. 3.12. Creep-vs.-stress curves for 0.33 per cent carbon cast steel. From "Symposium on the Effect of Temperature on the Properties of Metals," courtesy of ASME and ASTM.

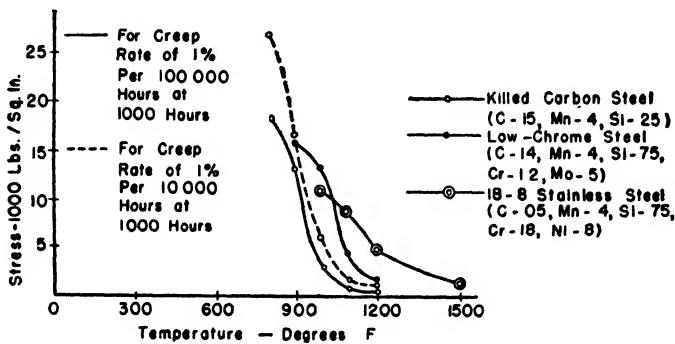


FIG. 3.13. Stress-vs.-temperature curves for three steels. Data from "Digest of Steels for High Temperature Service," courtesy Timken Roller Bearing Co.

for either a given total creep or for rupture are plotted. Fig. 3.14 illustrates a stress-vs.-time diagram and the creep-vs.-time curve from which it was derived. For this steel, the 1 per cent creep curve on log-log coordinates is a straight line. The rupture curve, however, is

composed of two straight lines — the slope changing at about 160 hr. Examination has shown this bend to take place when intergranular oxidation commences. For this particular steel, the fracture is transcrystalline (ductile) until intergranular oxidation commences, after

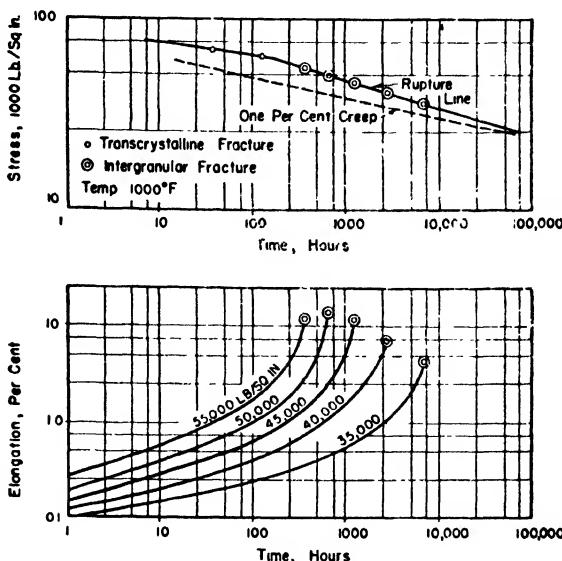


FIG. 3.14. A stress-vs.-time diagram and the creep-vs.-time diagram from which it was derived. Note the change in slope of the rupture line when intergranular oxidation occurs.

which it is of the intergranular (brittle) type. If the metal were in an oxygen-free atmosphere, there would be no bend in the curve — it would continue at its original slope.

Rupture data may be very important to the designer of high-temperature equipment. In Fig. 3.14, for example, the 1 per cent creep line is very close to the rupture line at 100,000 hr, so a part such as a boiler tube of this material, if designed with a permissible deformation of 1 per cent, would be very close to breaking after 100,000 hr of use.

**3.15. Relaxation (Constant-Strain) Tests.** If the loading applied to a metal part causes the total deformation (rather than the stress) to remain constant during long-time high-temperature service, the metal will be found to relax, i.e., its load-carrying ability will continuously decrease. This occurs in applications such as boiler rivets and turbine flange bolts. When a turbine flange is originally assembled, the bolts are drawn very tight. Often they are heated and tightened so their contraction on cooling will give added pressure between the

flanges. This of course stretches the bolt but its strain is normally elastic. When the turbine is in use, the combination of stress and high temperature in the bolt causes slippage on interatomic planes. The stress is slowly relieved and distributed and the bolt gradually loosens or relaxes. Although the original strain in the bolt was entirely elastic, part of this elastic strain is gradually changed into plastic strain. This decreases the stress in the bolt, and the pressure between the flanges

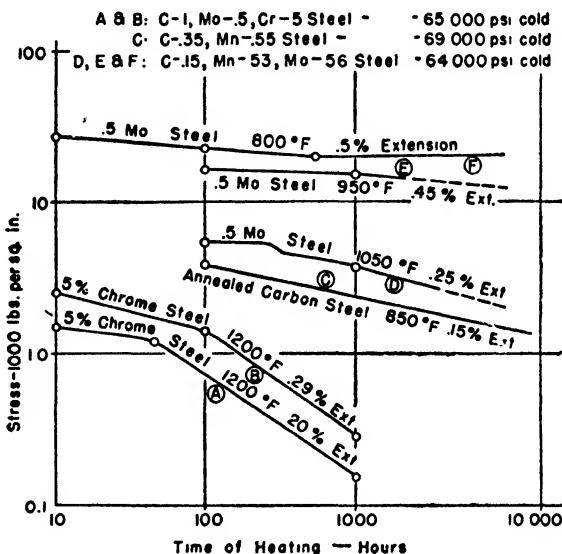


FIG. 3.15. Relaxation test data taken at constant total strain and constant temperature for three steels. The curves show the reduction of elastic stress with time.

becomes less. If a turbine is to be built for 9 years' uninterrupted service, the pressure between its flanges at the end of that time should be the criterion for the original design and assembly. Choice of proper allowances requires tests showing the relaxation of the bolt material with time. Tightening the bolts during service will of course change the relaxation conditions, and this effect is now being studied.

The results of relaxation tests at constant strain and temperature on several steels are shown in Fig. 3.15. The remanent stress is measured periodically during the test and plotted as a function of time (usually on log-log coordinates). This type of curve permits direct determination of the *original* stress required to provide a given *remanent* stress after the required duration of high-temperature service. For example, a joint held by a 5 per cent chrome-steel bolt at a stress of 1450 lb per sq in. (0.20 per cent ext.) after 10 hr of heating at 1200 F (curve A)

had a stress of only 150 lb per sq in. when the heating was continued for 1000 hr. If its stress were 2450 lb per sq in. (0.29 per cent ext.) after 10 hr (curve *B*), however, it would still have a stress of 280 lb per sq in. after 1000 hr at the same temperature. The shape of these curves, as with constant-stress curves, depends upon whether strain hardening or crystal repair predominates. If the steel tends to crystal repair (anneal), the curve bends downward as shown in *A*, *B*, *D*, and *E*. If the metal reaches a steady state in which strain hardening causes the relaxation to cease, the curve will bend up and become nearly level (curve *F*). In 10,000 hr at 850 F, the carbon steel (curve *C*) has shown neither tendency.

**3.16. Discussion.** There are many variables which apparently affect creep, but correlation of numerous data on various types of steels indicates that few rules can be established. The effects of the following conditions are so great, however, that they are usually observable in all tests.

(1) The alloying elements, nickel and manganese, which enter into solid solution in ferrite and the carbide-forming elements molybdenum, tungsten, vanadium, and chromium are all effective in raising the creep resistance of steel at temperatures below the lowest temperature of recrystallization. At temperatures higher than that for recrystallization, the carbide-forming elements are most beneficial (they are listed in the order of decreasing effectiveness).

(2) At temperatures above the lowest temperature of recrystallization, a coarse-grained steel gives better creep resistance than a fine-grained structure, whereas at temperatures below that point, the fine-grained steel is superior. Below 900 F, therefore, cast carbon and molybdenum steels are inferior in creep resistance to the wrought grades.

(3) Spheroidization and graphitization, caused by the continued heating, decrease creep strength.

(4) The creep resistance of silicon- and silicon-aluminum-killed (deoxidized) steels is changed little by variations in heat treatment, and above 900 F these steels are better in creep than aluminum-killed steels.

(5) The rimmed (not deoxidized) steels are inferior to killed steels.

(6) Medium-carbon (0.4 per cent C) steel is superior both to high-carbon steel and to very low carbon steel.

It must be remembered that prolonged heating, even though not accompanied by stress, often brings about metallurgical changes in a metal, sometimes causing changes in the actual outer dimensions of the metal piece. This is not creep itself, but is superimposed upon it and increases the complexities of studying creep.

The long time necessary to conduct creep tests has led to searches for accelerated tests, but none have proved satisfactory. As an alternative, methods of extrapolation have been used. Extrapolations from data on tests that have not completed the first stage give excessive values of predicted creep. The extrapolations of creep data carried well into the second stages are also of dubious value because they do not in themselves give assurance that the metal will not enter the third stage of creep during long-time service, although a small creep allowance (1 per cent or less) ordinarily gives adequate protection against such an occurrence. Some 100,000 hr (11½ yr) creep tests were completed August 1942. These eliminate the necessity for extrapolation on the materials tested, but, unfortunately, new materials must be judged and even applied before complete creep tests can be made.

### CYCLIC LOADS

Most structures and machines are subjected to loads, and therefore stresses, which are not steady or static. Even a bridge or a building, which may be thought to be under static loading, supports loads which vary with the seasons (heat, wind, snow, rain, etc.) and with traffic. Some of the properties determined as a measure of a metal's resistance to cyclic or varying loads are mechanical hysteresis, damping capacity, endurance, wear resistance, cutting hardness, and machinability. These properties are discussed in the order named.

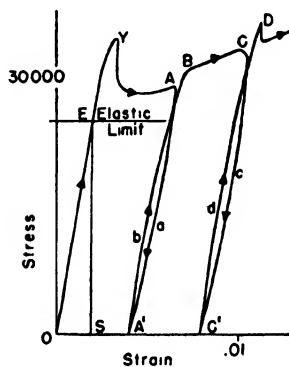


FIG. 3.16. Reloading stress-strain curve for mild steel.

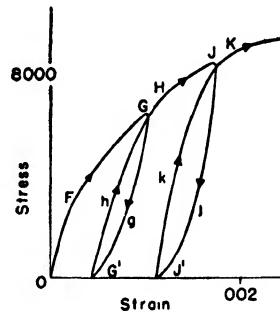


FIG. 3.17. Reloading stress-strain curve for annealed copper.

**3.17. Mechanical Hysteresis.** The stress-strain curve for a ductile steel, stressed slowly enough so the reaction forces always equal the load applied, will be similar to Fig. 3.16. If at *A* the load is decreased to zero, the stress-strain curve will follow *AaA'*, which is nearly, but

not quite, parallel to  $OE$ . When the steel is then reloaded, it will follow curve  $A'bB$ , which is a little to the left of  $AaA'$ . The area enclosed is called a "hysteresis loop" and is equal to the energy per unit volume transformed into heat during the stress cycle. Because of the work hardening properties of metal, the elastic limit and yield point  $B$  on curve  $A'bB$  will be slightly raised as shown. If deformation and stress are continued to point  $C$  and then relieved, a curve  $CcC'$ , similar to  $AaA'$ , will result. If the metal is allowed to rest for several days at point  $C'$ , it will "recover" slightly and the yield point will be increased to  $D$  as shown. Similar curves for copper are shown in Fig. 3.17. Note that work hardening is evidenced in it also and that it converts more energy into heat than the steel.

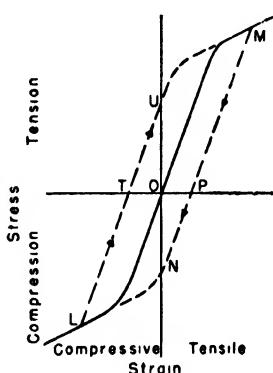


FIG. 3.18. Hysteresis loop caused by reversed cyclic load. The width of the loop is greatly exaggerated in this figure.

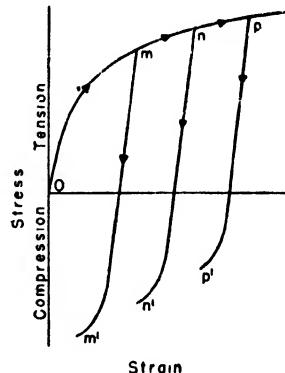


FIG. 3.19. Effect of reversing the load after stressing in tension beyond the elastic limit.

If the stress is completely reversed, loops as shown in Fig. 3.18 will result.  $LOM$  is the static stress-strain curve of the metal. If at stress  $M$  the stress is completely reversed, curve  $MPNL$  will result. Another complete reversal will bring the stress back to  $M$  along curve  $LTUM$ . This loop is much exaggerated in width — the metal would soon break if reverse-stressed so far beyond its elastic limit.  $OP$  and  $OT$  represent remanent strains (permanent sets) in the metal when the stress is reduced to zero from tension and from compression respectively.  $ON$  and  $OU$  represent "hysteresis stresses" necessary to reduce the tensile and compressive strains, respectively, to zero.

Hysteresis loops are detectable in steel at reversed stresses as low as  $\pm 1500$  lb per sq in., indicating that a precise elastic limit for steel is very low, or may be absent. If a metal tends to anneal (e.g., lead), the loop

may become larger as the loading is repeated, but in steel, the work hardening causes the loop to remain small in spite of repetition. After a large tensile deformation such as  $Om$ ,  $On$ , or  $Op$  (Fig. 3.19) a reversal of loading results in curves  $mm'$ ,  $nn'$ , or  $pp'$ , indicating a continuous decrease in the compressive elastic limit as greater and greater tensile stress is allowed in the load cycle.

**3.18. Damping Capacity.** A metal which has a large mechanical hysteresis loop and converts strain energy rapidly into heat energy causes high mechanical "damping"; in other words, it absorbs vibrations. This characteristic is often desirable in metal and accounts for the use of cast iron (a good damper) for machine- and steam-hammer-bases and for some crankshafts. From other considerations, cast iron is the last material that one might expect to make a crankshaft of, but where quietness is important, it is sometimes used. The long-continued "clang" of steel and "ring" of hard brass and Duralumin when struck indicate that vibrations in them persist because of low damping.

**3.19. Endurance.** If the variations of applied stress are large and numerous enough, a metal may fail even though the maximum applied stress is considerably less than the static strength of the material. This phenomenon is known as *fatigue failure*. Inspection of a great many of these fractures has shown that they invariably start as a minute crack at some point of high stress. With repetitions of loading this crack (called *fatigue nucleus*) spreads until the remaining cross-section of metal becomes too small to support the load, even in a static condition, at which time the part breaks.

The fracture is coarsely crystalline, similar to a static break in cast iron or brittle steel. This appearance and the seemingly characteristic suddenness with which failure occurs gave some support to the former theory that cold crystallization was the cause of failure. But it has been shown by many experts that this idea is incorrect and that the sudden break displays the normal crystalline structure of the material which in a static test is disguised to some extent by the distortion of the piece. The crystalline appearance is normally present only in the section which suffered the final break. The rest of the crack is usually smooth, owing to continuous rubbing of the sides of the crack during progressive fracture and possibly also to oxidation.

**3.20. Endurance Tests.** Tests of this type which result in fracture are usually called fatigue tests, whereas those which do not cause fracture are called endurance tests. In reporting these tests, both the variation of the stress and the kind or kinds of stress must be stated.

There are four general types of stress variations: reversed, alternated, repeated, and pulsated, as illustrated in Fig. 3.20. They may be desig-

nated either by indicating the maximum positive stress and the stress range, or by designating a mean steady stress and a superimposed fluctuating stress which gives the correct stress cycle.

Unidirectional tension, compression, or shear stresses produced by axial, bending, shear or torsional loading, or some combination of these may be employed. Most endurance tests, however, are made by bending a smooth rotating cantilever-beam specimen. Neglecting the vertical shear,<sup>1</sup> this loading pro-

duces, at any point in the beam, a completely reversing stress, from a maximum in tension to the same maximum in compression, and back again. For complete data on one metal, a number of specimens are tested under different loads. The tests are summarized by plotting the maximum stress on each specimen versus the number of stress cycles required to cause failure. Such a curve is called an *S-N* curve. On log-log coordinates, it is usually a straight sloping line down to some value at which it bends toward the horizontal, either gradually or sharply, depending upon the metal (see Fig. 3.21).

*Fatigue Strength.* Any point on the *S-N* curve to the left of the bend or "knee" indicates a limiting stress called the *fatigue strength*, which will cause fracture in the corresponding number of stress cycles. On curve *F*, Fig. 3.21, for example, 15,000 lb per sq in. is the fatigue strength for 100,000 cycles of reversed bending of gray cast iron.

*Endurance Limit.* As the severity of the stress variation is reduced, the metal will withstand a larger number of stress cycles before fracture. The limiting stress below which the metal will withstand without fracture an indefinitely large number of cycles of stress is called the *endurance limit*. This stress corresponds to the asymptote of the *S-N* curve, but for most purposes it is considered equal to the stress at the sharp bend in the curve. The endurance limit can be established for most

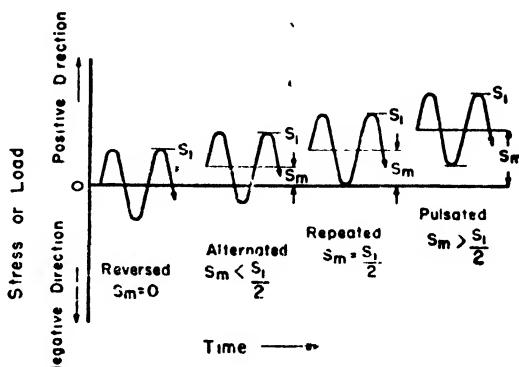


FIG. 3.20 Designations for four different types of stress variations.

<sup>1</sup> If the beam is supported at both ends and loaded with two symmetrical loads, pure bending may be produced in a test section between the innermost loads or supports. Specimens of this type are used to avoid the shear present in a cantilever beam specimen.

steels in about 10 million cycles, but for the nonferrous metals, 500 million cycles is often necessary because the  $S-N$  curves do not show a pronounced knee. It may even be entirely absent, as is shown for Duralumin, curve *E*, Fig. 3.21.

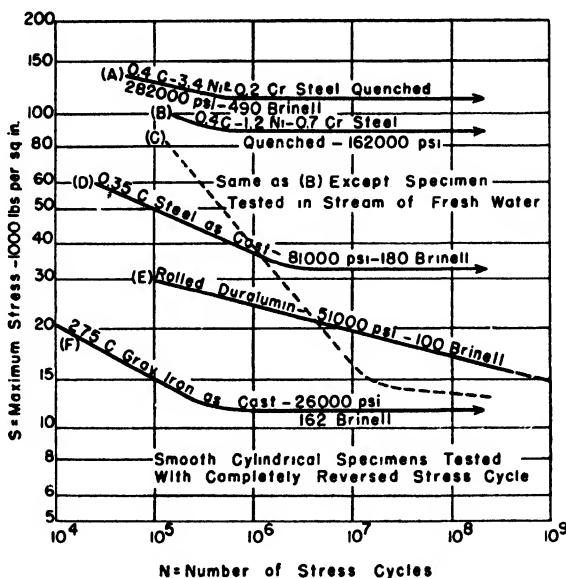


FIG. 3.21.  $S-N$  curves for some common metals. The values of stress on the curves are short-time tensile strengths. Data from "The Fatigue of Metals," by H. F. Moore and J. B. Kommers.

**3.21. Effect of Stress Concentrations on Endurance.** Polished, smooth specimens are used in laboratory endurance tests, and the stresses present are calculated on the assumption that there are no stress concentrations. This is seldom the case in practice since "stress-raisers" are present in the form of re-entrant corners, holes, changes in sections, slag inclusions, residual heat treatment stresses, notches, tool marks, mill scale, scratches, welds, press fits, etc. Under repeated loading of sufficient magnitude, a minute fatigue crack will appear, usually at one or more of these stress-raisers and will progressively increase in size until failure occurs. The *average* stress carried by the part may be well below the endurance limit, but, nevertheless, if a stress above the endurance limit exists at some point in the part, progressive failure will start.

A good many of the stress-raisers are surface effects, and, in fatigue, start cracks on the surface. This suggests that fatigue nuclei can be

detected by periodic inspection of parts in service, thereby permitting removal of faulty or damaged parts before actual failure occurs. A number of disadvantages offset this advantage: the possibility of inspecting parts in service must necessarily be infrequent in terms of the cycles of a load applied; cracks may be very difficult to detect; and fracture may occur very soon after the crack forms, thus allowing little time for detection and replacement. For these reasons preventive measures are by far the better cure. The first step is to properly handle the necessary stress-raiser in the design, and then to insist on proper heat treatment, high quality machine work, careful inspection before the part is accepted for service, and careful maintenance during its use.

The designer may take account of stress concentrations (other than those due to faulty workmanship) by (1) applying a correction factor to the endurance limits obtained with a smooth specimen of the material, (2) using as the design endurance limit a value obtained from test specimens similar to the part, or (3) designing in such a way that the maximum concentrated stress is below the endurance limit of the material.

Correction factors for method 1 are available for some simple types of stress-raiser such as holes and notches, but this method has the handicap that only a few types have been tested and the available data are insufficient for a good many design problems. Method 2 is the most accurate of all the methods if the specimen can be made representative. It has the disadvantages of expense and delay. Method 3 at first sounds like the best because extensive photoelastic studies of stress concentrations are available. This method, however, is usually over-conservative (in designs involving only a small number of load cycles) owing to the beneficial effects of plasticity in the regions of high stress concentration. Fatigue cracks advance without producing noticeable distortion, so the superiority of one material over another is not due alone to plasticity but probably more to a property called *crackless plasticity*, which apparently permits microscopic or submicroscopic yielding at the region of stress concentration without forming a crack.

All is not necessarily lost when a crack does form in the material, because under some conditions its propagation may be sufficiently limited so adequate life may be obtained from the part. The factors which determine the "period of grace" are the *notch sensitivity* of the material, the size of the part, i.e., the distance the crack must propagate, and the amount by which the stress exceeds the endurance limit. The life after initial damage may be particularly long if the stress which

caused the damage was due to some heavy overload, quite large in comparison with the normal operating stress.

Notch sensitivity increases in general with the hardness of steels and with cold working of both the steels and the nonferrous metals. There seems to be no direct correlation between notch sensitivity and ductility. Annealed copper is very notch sensitive, but brittle cast iron is not, nor is stainless steel, which has good ductility, although it may be influenced more by its great work hardenability. There seems to be no direct correlation of either notch sensitivity or crackless plasticity with other mechanical properties; but the shape of the stress-strain diagram, the damping properties, the modulus of elasticity, and the work hardening properties all seem to be involved. No short-cut tests or correlations can therefore be used for determining the endurance of a material; fatigue tests must be employed.

**3.22. Effect of Stress Cycle on Endurance.** When endurance data for the actual stress cycle of a proposed design are not available, the permissible cyclic stress and superimposed steady stress may be estimated by diagrams such as those proposed by Johnson and Goodman, Launhardt and Weyrauch, Howell, Gerber, and others.

*Goodman's Law.* To define the region of fatigue failure for stress cycles imposed on mean loads between zero and the ultimate strength, Goodman proposed a straight line relationship which may be represented as shown in Fig. 3.22. This law can be stated mathematically by the equation

$$S_r = S_e \left( 1 - \frac{S_m}{S_u} \right)$$

where  $S_r$  = one-half the total amplitude of the stress range,

$S_e$  = the endurance limit found by the reversed loading test,

$S_m$  = the mean value of the fluctuating stress,

$S_u$  = the static ultimate strength of the metal for the same type of stress.

This equation gives endurance limits for the calculated combination of stresses. If only a limited number of cycles is expected, the fatigue strength for that number can be used in place of the endurance limit. Torsion, axial tension, and bending tests show that higher-than-calculated maximum stress can be supported at low values of mean stress, indicating that Goodman's law is conservative.

*Gerber's Law.* Gerber proposed a parabolic relationship for the above stress values and still retained the two end points. His law is expressed

by the equation

$$S_r = S_e \left[ 1 - \left( \frac{S_m}{S_u} \right)^2 \right]$$

where the symbols have the same meaning as before. The end points of Gerber's law are exact, but mid-values of mean stress include stress combinations which may cause failure.

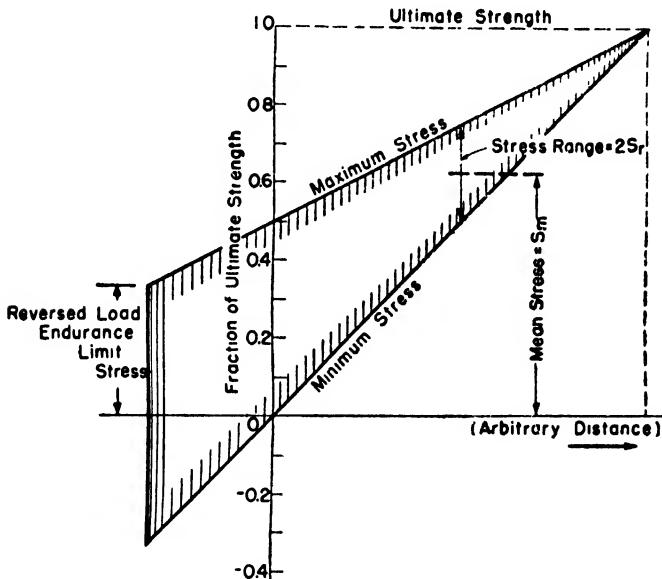


FIG. 3.22. Graphical representation of limiting values of stress range and superimposed mean stress according to Goodman's law.

**Yield Strength Law.** Parts designed to the limiting conditions of both the Goodman and the Gerber laws will be subject to some permanent deformation. Normally this will occur on the first cycle of stress, and will not increase if the maximum stress is not raised. In some designs, such as a shaft supporting torsion, this deformation may be permitted without hindering the functioning of the part. However, in most parts subject to unbalanced stresses, a small permanent deformation may cause interference or improper operation which is considered failure even though fracture does not ensue. The upper stress limit for designs of this type is the static stress which produces the damaging permanent deformation. As the mean stress approaches this yield strength (or yield point), the permissible cyclic stress must become smaller and smaller. The yield strength law, illustrated in Fig. 3.23, was developed

for materials used in such designs. It may be expressed by the equation

$$S_r = S_e \left( 1 - \frac{S_m}{S_y} \right)$$

where  $S_y$  is the yield strength of the metal.

The dotted curve shown in Fig. 3.23 represents permissible maximum stresses determined by actual tests on a metal. Such a curve indicates the effect of work hardening, and although it varies for different materials, it shows the yield strength law to be conservative.

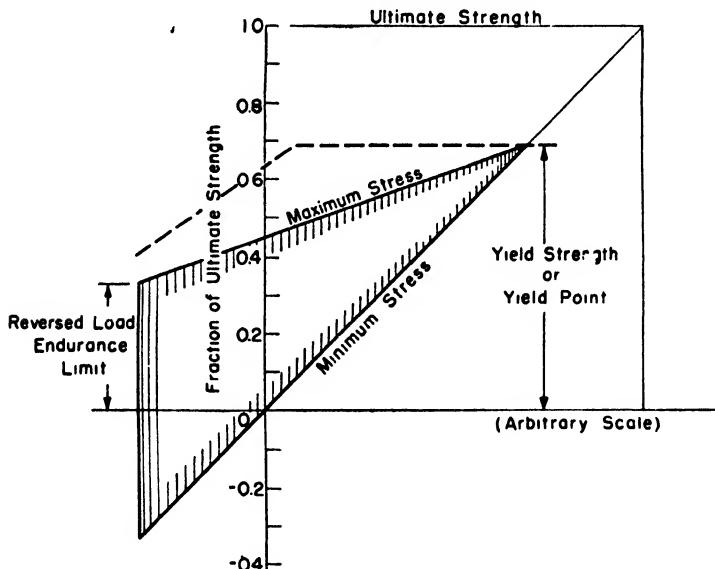


FIG. 3.23. Graphical representation of the yield strength law. The dotted curve represents the maximum permissible stress with the corresponding minimum stress, as determined by actual test for one ductile material.

**3.23. Discussion of Endurance Tests.** (1) The difficulty of extrapolating endurance test data makes it advisable, whenever possible, for the designer to use data on materials, shapes, and stress cycles similar to those involved in his design.

(2) Moderate elevation in temperature has only a minor effect on the endurance limit and may actually increase it by allowing plastic deformation when a metal might otherwise crack. A 0.14 per cent carbon steel, for example, showed a decrease of 9 per cent in static tensile strength at 750 F but had an increase of 16 per cent in 10-million-cycle fatigue strength at the same temperature. At high temperatures the endurance

seems to drop off in proportion to the ultimate strength, but test data are not numerous enough to be conclusive.

(3) Decreasing the effect of stress-raisers by introducing fillets is beneficial in steels and copper, has little effect in soft cast irons, and has usually less than 20 per cent benefit in the hardest of cast irons.

(4) Corrosion has a particularly harmful effect. The cyclic stress accelerates pitting, and the pitting accelerates failure. No endurance *limit* occurs; the stress that may be supported depends on the duration of loading.

(5) Cold rolling, flame hardening, and induction hardening increase the tensile fatigue strength of steel bars and axles for repeated and pulsated loads since the residual compressive stress in the surface decreases the actual tensile stress produced by the loading.

(6) Surface decarburization usually decreases tensile fatigue strength by decreasing hardness and leaving a tensile stress in the surface.

(7) Improved endurance may be obtained by cyaniding, carburizing, and nitriding. These operations change the surface material and this in part results in the improved resistance to fatigue. Nitriding also makes the material less notch sensitive, particularly for small notches.

(8) Welded-on "re-enforcements" may decrease the endurance of a part. Welds have practically every common type of stress-raiser. The surface is rough, there are internal stresses caused by the localized heating, and slag inclusions and blowholes may be in the weld metal.

(9) Present heat treating and hardening practice may introduce internal tensile stresses at the same places where stress concentration will take place during fatigue. These effects are usually additive and severe stress-raisers will result.

(10) The energy lost in mechanical hysteresis may produce considerable heating when the speed of cyclic loading is high. If the endurance limit is affected by an increase in temperature, corresponding effects will occur with increased speeds. In steels no effect is noticed up to approximately 30,000 cycles per min, but at somewhat higher speeds a slight increase in endurance occurs. Periodic resting during the life of the part seems to increase the endurance limit although tests are not conclusive.

(11) Understressing definitely increases the total number of stress cycles that can be supported, and it also raises the endurance limit somewhat if the stress is gradually increased from at least 10 per cent below the virgin endurance limit. Overstressing has the opposite effect as it produces damage, causing early failure.

**3.24. Wear Resistance.** The resistance of a material to wear and abrasion depends on many factors besides its hardness. These factors

include the nature and hardness of the abrading material, corrosion, and general service conditions. This explains why no standards for wear resistance have been set up. Those tests performed in practice are designed to duplicate service conditions as nearly as possible.

For good wear resistance in running or sliding contact, dissimilar material combinations or two pieces of the same metal having different indentation hardness are usually used. When loads are light and lubrication is used, a shot-blasted or somewhat roughened surface shows less wear than a very smooth surface because the roughened spots hold small reservoirs of lubricant which maintain lubrication between the contacting surfaces.

Among the old methods for designating abrasion or *scratch hardness* is the Mohs scale, which is based upon the relative hardness of the ten minerals: talc, rock salt, calcite, fluorite, apatite, orthoclase, quartz, topaz, corundum, and diamond, from the softest to the hardest. The hardness of other materials can be located on this scale by a scratch test, the harder material being capable of scratching the softer. For metals, particularly the steels, a file test is frequently used in the same way in the shop to ascertain relative hardness. This method depends to some extent on the skill of the shopman to perform the test consistently. There are also other scratch testing methods employing metal or diamond points, and either measuring the scratch width for a given load or the load for a standard scratch width.

**3.25. Cutting Hardness and Machinability.** Cutting hardness tests may be of two kinds: those applied to cutting tools and those applied to materials that are to be machined. The latter determine resistance to cutting and are called *machinability tests*. No tests of either type have been developed which may be considered wholly reliable, but many comparative shop runs are used to obtain the information needed in specific cases.

One reason for the difficulty in establishing comparative machinability tests is the difference in machining operations performed by different tools and machines. In some the metal is torn, in others it is sheared or abraded. Most testing has been done on lathe work, and in these tests the machinability is gauged by comparing the power required to remove a given quantity of material from a standard specimen with the best technique. Some tests have also been made on side milling, planing, and drilling.

Metals are sometimes alloyed to increase machinability. Sulphur is added to steel and lead is added to brass for this purpose, but part of the ductility is thereby sacrificed.

Ease of machining is not determined alone by hardness, but is greatly

influenced by toughness and by the tendency of a material to harden under cold work. A fairly soft but very tough steel, for example, will not machine as freely as one with somewhat greater hardness and less toughness. A misleading custom has grown up in shops where any difficulty with machining is expressed by saying that the metal is "too hard to machine." In this case the word "hard" is used not in the technical sense of hardness as measured, for example, by the Brinell machine, but as synonymous with "difficult." Frequently a material classed as too hard to machine is really too soft to machine readily. This softness and toughness result in a tendency of the metal to tear and flow ahead of the tool rather than to be cut cleanly.

### IMPACT LOADS

**3.26. Impact Loads and Tests.** Impact or shock loads differ from cyclic loads in two ways. First, the load is applied with appreciable velocity, usually sufficient to modify the characteristic response of the material; and second, the loading is seldom repeated, failure occurring in the first application if occurring at all. Fatigue, as discussed in the last section, is not a factor in impact strengths, but cyclic loads which cause fatigue may also be of high velocity. Some designs which involve high-energy impact loads are steam hammers, punching and forming machines, landing gear on airplanes, gun mounts, internal combustion engines, and numerous machinery and apparatus parts.

Impact testing is a comparatively new field of investigation, but it has been stimulated greatly by the necessity for finding materials to withstand the abuse of warfare. The first standardized tests were the Charpy and the Izod bending tests. More recently high velocity tensile tests have been developed and explosives have even been used to cause very high velocity shocks.

**3.27. Bending Impact Tests.** In the Charpy and Izod machines, a weighted pendulum is swung through an arc so as to fracture a carefully prepared specimen of the metal. The number of foot-pounds of energy required for fracture (determined from the difference in potential energy in the pendulum before and after the blow) is considered a measure of the *impact strength*. The only difference between the two tests is the shape of the specimen and the type of support used. The Charpy specimen is supported at both ends, and struck opposite a notch made by drilling a through hole and relieving it on one side. The Izod specimen is of the end-loaded cantilever-beam type and contains a "V" notch on the loaded side. Both are sketched in Fig. 3.24. They give quite different results, hence the type used should be identified when quoting impact strengths.

The notches act as stress-raisers, so the tests also test notch sensitivity. In fact, in many metals the velocity of loading seems to have little effect. By comparison, changing the shape or the proportions of the notch has a great effect. For example, doubling the cross-section by eliminating the notch much more than doubles the impact strength. But doubling the area by doubling the width of the specimen, and maintaining the notch, has varying effects. Actually the energy required for fracture may be decreased instead of doubled as might be expected.

To a certain extent, these tests also indicate the ability of the material to support combined (three-dimensional) stress, since the loading and shape cause a complex triaxial stress condition.

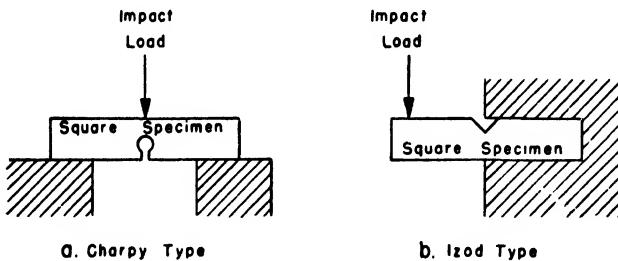


FIG. 3.24. Bending impact test specimens.

The bending impact tests are thus a measure of the metal's sensitivity to notches and its ability to support combined stresses. The tests are of qualitative rather than quantitative value, but both single and double width specimens must be used before the true quality of the metal can be evaluated. Sensitivity to notches is apt to occur at low temperatures (in steel, anywhere from +200 to -200 F), hence these tests are of great importance in locating the minimum working temperature for metals subject to shock loading.

**3.28. Tensile Impact Tests.** The machine for measuring the resistance of a material to high velocity tensile impacts was developed in 1935 by H. C. Mann. In it a variable speed flywheel delivers a tensile impact to a test bar similar to the bars used in ordinary tensile testing machines (see Fig. 3.25). The advantage of the test is that it permits study of the impact strength of a metal under a unidirectional stress and at various velocities. The effect of velocity on several steels is plotted in Fig. 3.26. Note that: (a) For several metals, at velocities up to 30 or 40 ft per sec, there is a rapid rise in the energy required to fracture the metal and then a straight, slowly rising curve for greater velocities. (b) Malleable iron, and normalized and drawn carbon steel have a peculiar dip in their curves; and the curve for stainless steel

shows it to require more energy for static rupture than for rupture at moderate impact velocities (25 ft per sec). An explanation for the

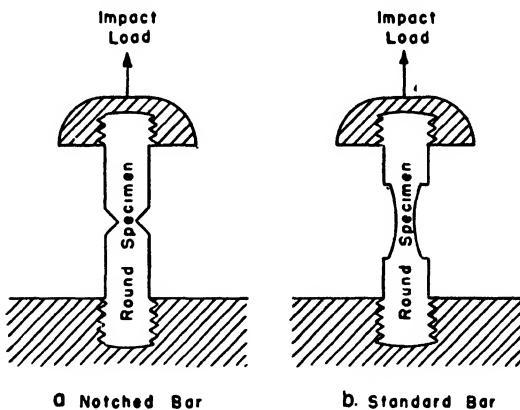


FIG. 3.25. Test specimens for Mann type of tensile impact.

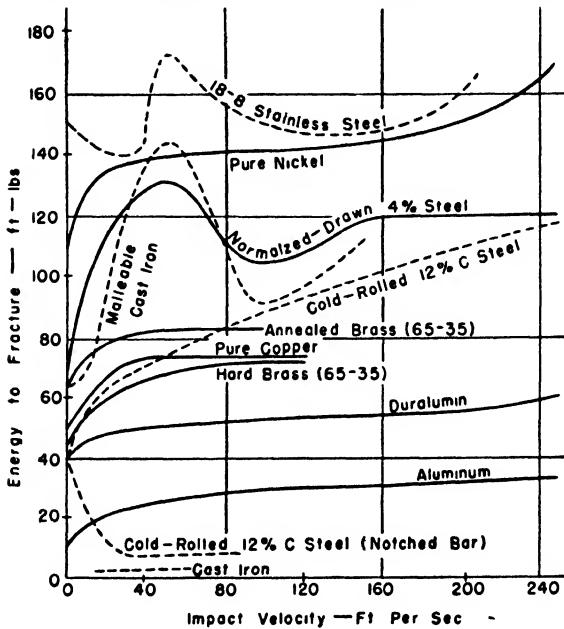


FIG. 3.26. Energy to fracture metals at various impact velocities. "Zero velocity" impact corresponds to the static tensile test.

shape of these curves has not yet been agreed upon. (c) Heat treatment ordinarily has an effect on impact resistance (see curves for brass).

At present it seems impossible to predict the shape of the energy-velocity curve for a metal.

Curves of elongation versus velocity are shown in Fig. 3.27 for the same metals as illustrated in Fig. 3.26. In general, the elongation at

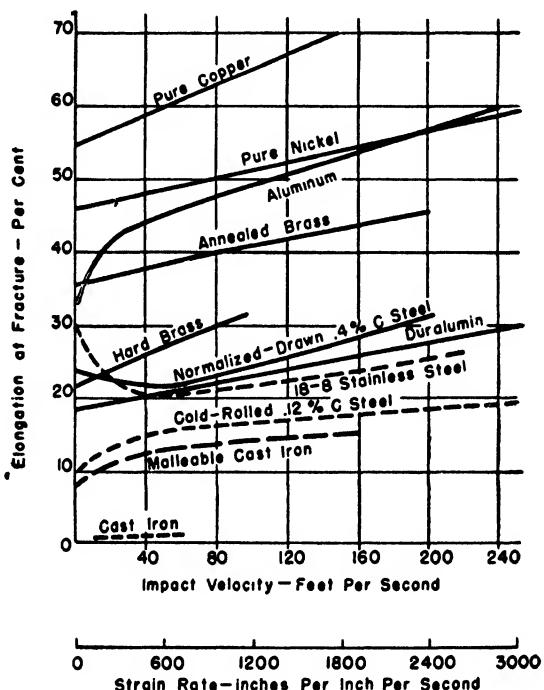


FIG. 3.27. Ductility of metals at various impact velocities.

fracture of the metal test bars increases gradually as velocity increases. A larger deformation allows a metal to absorb more energy before fracture, so these ductility curves have a general upward trend the same as the energy curves, but no quantitative comparison is possible.

The shape of the tensile stress-strain curve is greatly affected by the rate at which stress is applied. Ordinary tensile tests are conducted at a strain rate of approximately 0.0003 in. per in. per sec and the curve is relatively smooth. If the stress is applied at a high velocity, however, tension and compression waves are set up which travel rapidly back and forth within the metal and cause the stress to oscillate as shown in Fig. 3.28. Only recently has the determination of these curves been successful, so their shapes have not been thoroughly explained.

### DESIGN

**3.29. Design Method.** The steps taken by the designer in the solution of a design problem show much variation both with the individual and with the specific problem. But, in a general way, the customary procedure may be outlined as follows: (*a*) determination of required function of the design (this is the most important step, and hasty or faulty analysis here accounts for a large proportion of the

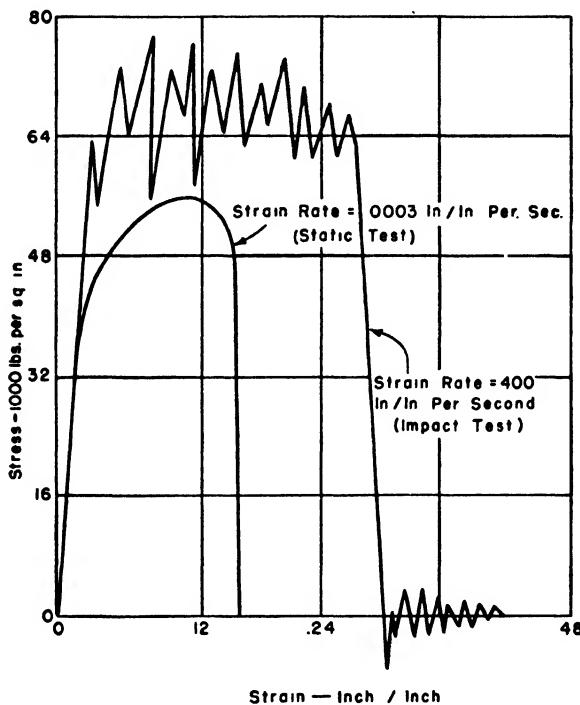


FIG. 3.28. Tensile stress-strain curves for Duralumin loaded at two different speeds.

failures); (*b*) review of available "power"; (*c*) adaptation of "power" to a design scheme or plan; (*d*) consideration of performance, realization of limiting factors; (*e*) choice of design elements in view of required performance; (*f*) choice of materials and proportions; (*g*) consideration of methods of manufacturing; and (*h*) decisions, compromises, and choice of final arrangement.

These steps normally are not taken in succession. Instead there is much reconsideration, much re-evaluation of the first factors considered as further study modifies the situation. This is particularly true of steps *c* to *g*. Several designs may be created, and the merits

of each weighed before final choice in step *h*; or one design may predominate and be progressively improved until satisfactory.

Data on mechanical properties of metals are essential to step *f*. Sometimes very careful analysis is required before these data may be used properly. Other times, depending on past experience and the operating function, an instant choice can be made. In any event, the design problem of this step is to take every possible advantage of the points of superiority of a metal and to compromise to compensate for the properties in which the metal is inferior. The character of the mechanism, the loads and other conditions it will meet in service, and the requirements for its production will profoundly affect the approach to the problem.

Some of the factors involved in this design procedure and associated with the mechanical properties are considered briefly.

**3.30. Performance and Limiting Factors.** Probably the first factor considered is the nature and the magnitude of the expected load. In the design of a steam boiler, the static pressure load is probably the principal one to be considered, whereas in the design of the rotor for an induction motor, consideration must be given to overloads, overspeeds, unbalanced torques caused by open-phase operation, vibration caused by dynamic unbalance, and heavy transient forces caused by high starting currents.

Other limiting factors may be high or low temperature, corrosion, current-carrying capacity, damping capacity, work hardenability, stability against buckling, etc.

**3.31. Materials and Proportions.** The necessary performance and the general nature of each part of the design having been decided, the material to be used and its proportions are next chosen. The choice of a material and its proportions go hand in hand, since the material strength and stiffness must influence the proportions, and the facility with which the material can be handled in manufacturing processes limits the shape.

**Damaging Stress.** Another factor to be considered in the choice of a material is its *damaging stress*. This stress is the minimum stress which, if exceeded, would render the material unfit for service before the end of its normal expected life. It depends upon the criterion of failure. The nature of the part determines whether this criterion shall be excessive permanent set (or creep), or excessive strain hardening, or actual rupture.

**Working Stress.** The actual stress which the part will be designed to handle is termed its *working stress*. Ideally, this stress would be chosen as just slightly below the damaging stress, and maximum strength

of the material would then be used. In practice, however, working stresses are designed to be much lower than the damaging stress.

*Factor of Safety.* The ratio of damaging stress to working stress is called the *factor of safety*. If the designer were to know with exactness the properties of the material, the nature and magnitude of the expected load, and the way the load would distribute itself within the material, he could design, using a factor of safety of unity. Actually he uses factors of safety from 1.2 up to 20. Some of the conditions which affect the choice of a factor of safety are:

(a) Variations in the properties of the material because of structural heterogeneity, possible presence of inclusions and blowholes, and size effect.

(b) Inaccuracies in determining the magnitude and distribution of load stresses. Also under this classification are the errors introduced by the assumptions underlying the theory used, and the assumptions made to reduce the actual problem to one that could be handled by mathematical theory.

(c) Residual heat-treatment and cold-working stresses, stresses caused by assembly or thermal gradients, or stresses due to handling.

(d) Variations in time effects, such as uncertainties in creep, brittleness, corrosion, fatigue.

(e) Economy of weight or material.

(f) Risk of life or financial loss that is involved. Sometimes members are provided to assume the load in case of failure of the main load carrier; for example, the double fork for motorcycles.

(g) Quality of workmanship (fits, tolerances, absence of tool marks, etc.).

Some factors of safety in common use are as follows:

(1) For static loading of steels and other ductile metals, if the elastic limit is the damaging stress, the factor of safety ( $N$ ) is usually chosen as 2. If stress-raisers are present which may relieve themselves by ductile flow of the metal, or if the severest overload instead of the normal load has been used in computing damaging stress,  $N$  may be less than 2, the working stress being the maximum stress at the stress-raiser, or caused by the overload.

(2) In airplane design  $a$  and  $b$  above are carefully controlled and determined, and consequently good results are obtained from the use of  $N$ 's below 1.5.

(3) For static loading of cast iron, the ultimate strength is usually the damaging stress, and factors from 4 to 10 are chosen.

(4) Under fatiguing conditions, fatigue strength or endurance limit is the damaging stress, and  $N$  is about 2.5 or 3 where conditions are

TABLE 3.1. MECHANICAL

Name	Composition	Treatment	Elongation in 2 in., %	Mod. of Elast. million lbs./sq. in.		Poisson's Ratio $\sigma$
				Tens. and Compr. E	Shear G	
Aluminum, commercially pure	99 Al	2 SO Ann 2 SH Hard 17 SO Ann 17 SH Hard 324 HT 305 701 Soft	35 5 20 22 12 2 30	9 5 9 5 10 5 10 5 10 10 3	3 8 3 8 4 4 4 4	0.36 0.36
Duralumin	92 Al, 4 Cu, 0.5 Mg, 0.5 Mn					
Al-Mg casting alloy	90 Al, 10 Mg					
Al-Si die casting alloy	87 Al, 13 Si					
Bronze 88-9-3	88 Al, 9 Cu, 3 Fe					
Copper, commercially pure	99.9 Cu	Soft Hard Ann. CW	25 8 62 7	16 16 15 14	5 5	0.33 0.33
High brass	65 Cu, 35 Zn					
Cu-Ni alloy	55 Cu, 45 Ni					
Bearing metal	80 Cu, 10 Pb					
Gunmetal	88 Cu, 9 Sn, 3 Zn					
Gold, 14 k yellow	58 Au, 11 Ag, 26 Cu	Ann. and A	11 5			
Lead, white bearing metal	75 Pb, 14 Sb, 10 Sn		25			
Magnesium, pure	99.9 Mg	Rolled	4			
Dowmetal A	92 Mg, 8 Al					
Dowmetal H	90 Mg, 6 Al, 3 Zn	HT-A	5	6 5		
Nickel, commercially pure	99.4 Ni	Grade A Ann Grade A CD Ann. CD-HT Cast	45 30 40 20 2	30 30 26 26 26	11 11 9 5 9 5	
Monel K	66 Ni, 29 Cu, 3 Al					
Monel S	63 Ni, 30 Cu, 4 Si, 2 Fe					
Nichrome V	80 Ni, 20 Cr					
Tin, commercial	99.9 Sn					
Babbitt 5	65 Sn, 18 Pb, 15 Sb, 2 Cu					0.33
Zinc, Cu-Hardened	99 Zn, 1 Cu					
Die casting alloy	96 Zn, 4 Al	903	5	13		
Cast iron, class 20	93 Fe, 4 C, 2 Si					
Class 50	93.5 Fe, 3.5 C, 2 Si					
High nickel	73 Fe, 15 Ni, 6 Cu, 3 C					
White	96 Fe, 2 C, 1 Si					
Malleable	96 Fe, 2 C, 1 Si					
Cast Steel, medium	98.5 Fe, 0.3 C	1030 Ann.	20	30		
Wrought Iron	98 Fe, 2 Slag		35	28	12	
Steel, mild structural	99 Fe, 0.2 C	1020 HR 1020 CD 1040 HR 1040 HT	24 20 18 23	28 28 28 28	13	0.26
Machine	98.7 Fe, 0.4 C					0.26
Tool	98.5 Fe, 0.95 C	1095	15	28		
Spring	98.5 Fe, 1.1 C	10110		28 5		
Ni steel	95 Fe, 3.5 Ni, 0.35 C	2335 HT 2335 HT	25 18	28 5 28 5		
Hi-steel	98 Fe, 1 Cu, 0.5 Ni, 0.08 C					
Manten	97 Fe, 1.6 Mn, 0.3 Cu, 0.25 C					
D8 Grade 1	98 Fe, 1.6 Cu, 1.2 Ni, 0.12 C					
Stainless Steel, Ni, Cr, Mo	95 Fe, 2.2 Ni, 0.9 Cr, 0.4 Mo	4340	22	28		
18-8	73 Fe, 18 Cr, 8 Ni, 0.15 C	347 Soft	45	29		
High Chrome	83 Fe, 17 Cr, 0.6 C	HT HT	12 2			

<sup>1</sup> If a metal has no yield point, its strength and offset are given.<sup>2</sup> Defined as stress which causes 25 per cent elongation.

A, Aged CD, Cold Drawn.

Ann., Annealed. HR, Hot Rolled.

HT, Heat Treated.

U, Unnotched.

# MATERIALS AND PROPORTIONS

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## PROPERTIES OF SOME COMMON METALS

Ultimate Strength 1000 lbs/sq in.			Yield Point or Yield Strength <sup>1</sup> 1000 lbs/sq in.			Elastic Limit <sup>2</sup> 1000 lbs/sq in.			Reversed Bend Endurance 1000 lbs/sq in.	Hardness Brinell	Impact Charpy
Tension	Com- pression	Shear	Tension	Com- pression	Shear	Tension	Com- pression	Shear			
13		9 5	5(0 002)			2			5	23	...
24		13	21(0 002)			12			8 5	44	...
26		18	10(0 002)			7					...
60		36	37(0 .002)			20					...
45	72	33	25(0 002)	26(0 002)					7	80	4 5
33		26	18(0 002)	18(0 002)					15	75	2
80		..	..			30			..	130	..
35		..							10	45	..
50		..	31(0 0002)						12	..	..
45		..	..						12	..	..
100		..	..			20			17	..	..
55		43				30			..	80	29
30		..	21(0 001)	14(0 001)					..	63	..
38	250	34	14(0 0001)	17(0 001)		10 5			13	65	10
110		..	105						..	190	..
215		..	..	3 5(0 0012)		2 5			..	23	..
25	40	14	9 5(0 0025)			2 5			..	40	..
34		..	12(0 0025)						7	..	..
38	50	18	18(0 002)						10	62	..
75		..	27(0 002)	26(0 002)					30	109	216
85		81	62(0 002)	58(0 002)		25			50	50	177
100		..	70(0 002)			50			..	45	160
150		..	115(0 002)			..			..	51	300
110		..	90(0 002)			..			..	..	300
110		..	63			..			..	..	4
2	..	..	..	5(0 0012)		0 2			..	5	..
215	..	..	..	..		3 7			..	22	..
30		..	..	..		..			..	..	..
40	60	31	..	..		5			..	70	20 U
22	190	33	..	..					10	100	Low
55	125	50	..	..					20	200	Low
30		..	..	..					..	..	..
50		..	..	..					..	400	Low
50		48	37	..		23			..	120	7
80		..	40	..					35	140	..
50		37	..	..					..	..	..
65		..	50	35					..	..	..
75		..	..	..		30			25	30	110
80		..	..	50					..	35	160
100		..	..	70					..	35	150
130		..	..	75					..	48	185
175	150	..	..	..		150			..	56	260
110		..	65	..		60			..	55	195
150		..	137	..					..	..	..
71	54	..	57	..					..	..	..
92		..	66	58					..	..	..
104		..	70	64					..	..	..
105	4 3	..	35	..					..	45	220
105		..	..	55					..	52	200
130		..	100	..					..	..	285
270		..	245	..					..	..	545

good, 3 or 4 in the presence of stress-raisers, and even more if corrosion may take place.

(5) Under combined stress conditions, factors of safety may be determined by various theories, such as the Mohr theory, the maximum shear theory, and the strain energy of distortion theory. This is a complex study and the designer should consult references on elasticity.

It may be seen that the factor of safety has a wide range of values and its choice depends ultimately upon the experience and good judgment of the designer. In many projects, the factors of safety are agreed upon at conferences among the engineers, designers, and contractors. A designer should not attempt to use factors too radically different from those which have been proved by experience, unless a very careful study of the variables indicates that reductions are feasible.

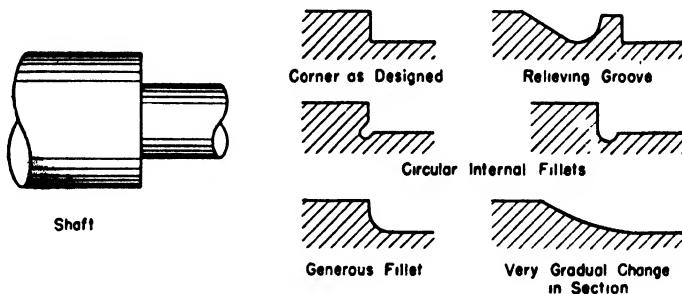


FIG. 3.29. Several methods for mitigating the stress concentration which occurs at a sharp change in section of a shaft subject to torsion or bending.

*Proportions.* The proportions of the part are chosen so it can perform its required functions without having the *maximum* stress exceed the working stress. Although stress concentrations may be relieved by plastic flow in some ductile metals, it is good practice to eliminate stress-raiser in so far as possible by the use of fillets, smooth contours, rounded edges, etc. An example of the possibilities (Fig. 3.29) is included; it illustrates several typical ways in which the stress concentration in a shaft under torsion or bending can be relieved.

*Stress Determination.* For the more simple shapes, the actual stress present can be calculated mathematically and the proportions established in that way. Frequently, however, the shape is complicated and does not lend itself to straightforward analysis. For these, the stress distribution, assuming perfect elasticity, may sometimes be obtained by photoelastic testing of a suitable transparent plastic model under polarized light. This method is particularly helpful for parts containing stress-raiser, although in ductile materials some yielding

may take place to reduce the stress concentration, thus permitting a larger load to be supported. A great amount of this type of testing has been done, so many data are available.

Other methods of determining maximum stresses of sample parts are the use of a brittle lacquer coated on the part, and the use of small carbon electric strain gages. The lacquer cracks when local yielding reaches some limiting value, thus indicating regions of high stress and strain. The strain gages are better as a measure of stress for a given strain but the points of stress concentration must be anticipated.

**3.32. Conclusion.** The subject of mechanical properties of metals is very broad and diversified and it has therefore been necessary to limit this chapter to only a brief discussion of the salient points. Over a period of years, the work of many colleges and industrial research groups has made available vast quantities of data. The stimulus provided by the war effort will no doubt add many data on new materials and on properties not formerly tested to any great degree. It is recommended to the designer who makes use of these data that they be employed with care. Lack of thorough evaluation of the meaning of the test properties with respect to the operation of the material in service can easily result in faulty application.

The designer is also urged to keep abreast of the developments. New developments seem particularly rapid and significant in this field and may make possible tomorrow something which is impossible today because a material having the necessary properties is not now available.

### REVIEW QUESTIONS

1. Explain the difference between the following:

- (a) Elastic limit and proportional limit.
- (b) Yield point and yield strength.
- (c) Toughness and resilience.
- (d) Endurance limit and fatigue strength.

2. A carbon steel motor shaft has been found to deflect too much in service. It has been suggested that an alloy steel shaft of the same size but having a higher elastic limit would remedy the trouble. Point out the fallacy.

3. What is the approximate Brinell hardness number of a mild steel whose static tensile strength is 70,000 lb per sq in.?

4. How do the strength and ductility of metals vary in general with temperatures above and below room temperature?

5. (a) What two structural changes in the material tend to balance each other during the second stage of creep? (b) What is the difference between creep rate and total creep?

6. Why is mechanical hysteresis important in materials for parts subject to vibration near their resonant frequency?

7. Describe how metals fail in fatigue.

8. Name six types of stress-raisers which increase the susceptibility of a part to fatigue failure.
9. What information does the engineer obtain from bending impact tests?
10. Define the factor of safety, and give several conditions which affect its value.

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## CHAPTER IV

### IRON AND STEEL

**4.1. Introduction.** This period in which we are living has been appropriately called the "Iron Age." No event in the history of civilization equals in importance the development of the art of producing iron and its alloy, steel. There is evidence that a few iron tools were in use in India, China, and Egypt over 4000 years ago. These early iron implements were probably produced by subjecting lumps of iron ore to long exposure to an ordinary campfire and then beating the extracted metallic iron into the desired shapes. This metal resembled wrought iron, since it could have dissolved very little carbon during the deoxidizing process.

Iron was used but little, however, until the invention of the blast furnace made large quantities of the metal available. This was followed by the invention of large-scale refining methods such as the Bessemer and open-hearth processes, which gave to mankind its most useful material, steel. Today the production of iron and steel is about fifteen times that of all other metals combined.

**4.2. Production of Iron and Steel.** *Iron* is the name given to pure ferrite, Fe, as well as to fused mixtures of this ferrite with large amounts (above 1.7 per cent) of carbon, these mixtures being known as *pig iron* and *cast iron*. Intermediate between pure iron and cast iron is *steel*, in which none of the carbon is in elemental form. Practically all of the carbon in steel is combined in the intermetallic compound, iron carbide.

Pig iron (produced from iron ore in the blast furnace) is the basic raw material from which all cast iron, wrought iron, and steel are made. Cast iron is obtained by slightly purifying the pig iron in a "cupola" or other furnace in which the composition of the iron can be varied; whereas wrought iron and steel are obtained by considerable furnace purification of the pig iron.

**4.3. The Blast Furnace.** The blast furnace, which is used to obtain pig iron by the chemical reduction (smelting) of iron ore, was invented in Germany about 1400. Since its invention, the original furnace has been improved and increased in size so that modern blast furnaces stand from 75 to 110 ft high and produce up to 1000 tons of iron per day. They operate continuously and need not be shut down for repairs oftener than once every 5 to 7 yr. The charge is put in at the top and

the molten iron and impurities are drawn off separately at the bottom as they accumulate.

The principal parts of the furnace are shown in Fig. 4.1. The hoppers at the top receive iron ore, limestone, and coke, and the gates are opened cyclically to admit this charge to the furnace. The ore contains iron in the form of  $\text{Fe}_2\text{O}_3$  (in hematite ore) or  $\text{Fe}_3\text{O}_4$  (in magnetite ore).

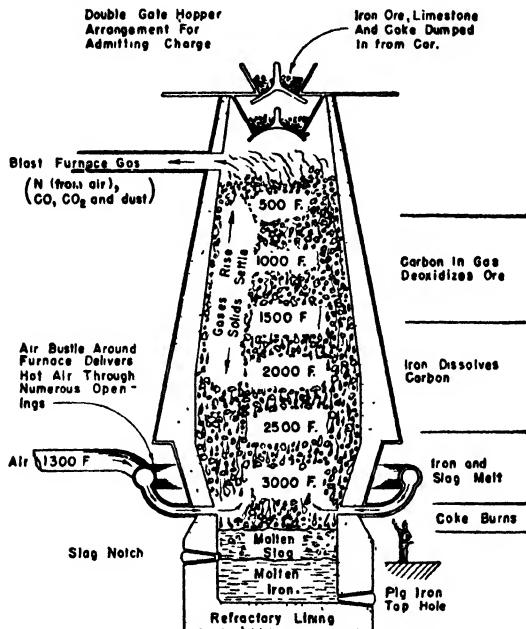


FIG. 4.1. Elementary cross-section of blast furnace ready for tapping. Slag notch will be opened and slag drawn off, then iron will be drawn from the tap hole. The supports and the cooling systems have been omitted.

The limestone helps reduce these iron oxides and unites with the ash of the coke and the impurities in the ore to form a *slag* which melts near the bottom of the furnace. The coke also helps reduce the iron oxides, furnishes carbon to saturate the iron, and ultimately burns in the lower part of the furnace, supplying heat to melt the iron and slag. This slag floats on top of the molten iron like cream on milk and is removed through the slag notch. A large volume of hot air is blown in at the bottom of the furnace to promote combustion of the coke and to help carry the gases upward. The temperatures are approximately as shown, although the heat is controlled to suit the nature of the ore being smelted.

**4.4. Theory of Chemical Reduction in the Blast Furnace.** The more important materials present in the blast furnace charge, except for

carbon, are shown in Fig. 4.2. The oxides are arranged in order of increasing stability; that is, the higher an oxide occurs on the scale the more difficult it is to reduce (deoxidize) and the more easily the corresponding element is oxidized. Lime ( $\text{CaO}$ ) is therefore the most "stable" oxide on the scale, whereas sulphur dioxide ( $\text{SO}_2$ ) is relatively unstable, only a small amount of heat being required to reduce it to the elements sulphur and oxygen. The elements appearing above iron will take oxygen from iron oxide. Silicon, for instance, is such a *reducing agent* (deoxidizer) for iron.

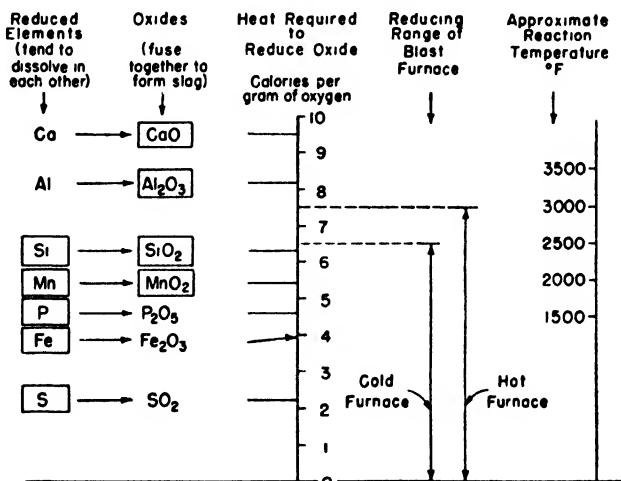


FIG. 4.2. Heats of formation of oxides present in the blast furnace and approximate reducing temperatures. Squares indicate substances which are normally present in the lower region of the blast furnace.

Carbon is not shown in Fig. 4.2 because its position changes, depending upon the temperature. At low temperatures carbon dioxide ( $\text{CO}_2$ ) is below  $\text{Fe}_2\text{O}_3$  in the scale, but at high temperatures it is above  $\text{P}_2\text{O}_5$ . The relative positions of the various oxides in Fig. 4.2 determine approximately the required reaction temperature in the blast furnace. In general, the more heat the reaction requires, the hotter the material must be in order to maintain good reaction speed.

The blast furnace operator makes use of two very important characteristics of the materials shown in this figure. First, the oxides collect together to form a slag and the pure, reduced elements dissolve in each other. Second, the slag when molten does not mix with the molten metal but, being lighter, floats on top.

It would be ideal if the iron oxide could be reduced to pure iron and all of the other impurities left in the form of oxides in the floating slag.

However, the heat of formation of the various oxides prevents this ideal reduction procedure. This can be explained as follows: Consider a blast furnace charge of iron ore and coke (no limestone). The ore and coke contain impurities in the form of S, SO<sub>2</sub>, P<sub>2</sub>O<sub>5</sub>, MnO<sub>2</sub>, SiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub>. If the temperature at a certain point in the blast furnace were just high enough to drive the oxygen out of the iron ore and leave pure Fe, P<sub>2</sub>O<sub>5</sub> and other higher oxides would remain in the slag, but the iron would dissolve sulphur because sulphur would also be entirely deoxidized at this temperature. This represents the situation about halfway down in the ordinary blast furnace. At this stage the iron is still solid; its reduction has taken place entirely in the solid state. As the furnace charge settles farther toward the bottom it becomes hotter and hotter. Phosphorus is reduced and dissolves in the iron, and then Mn and Si follow. Therefore, if iron ore and coke were the only materials used in the charge, the iron, by the time it reached the liquid state in the bottom of the furnace, would contain almost all of the S and P and quite a portion of the C, Mn, and Si. A molten slag of Al<sub>2</sub>O<sub>3</sub> and some SiO<sub>2</sub> and MnO would also appear at the bottom of the furnace, floating on top of the molten iron.

The amount of Si and Mn in pig iron can be minimized by operating the furnace "cold," i.e., by decreasing the reducing intensity of the furnace. The minimum temperature, however, is the melting point of iron. At this temperature, phosphorus is still reduced and the pig iron contains *all* of the phosphorus which entered the furnace.

A large amount of sulphur also enters the furnace in the coke, and since all of it would appear in the pig iron, it is prevented from doing so by adding limestone (CaCO<sub>3</sub>) to the charge. Part way down the furnace, the limestone liberates CO<sub>2</sub> and becomes lime (CaO) which is a very staple oxide (see Fig. 4.2). Some of the lime reduces the sulphur to CaS, however, which passes off in the slag. The lime accomplishes the further purpose of forming a free-flowing slag which melts and drips rapidly through the hot lower part of the furnace, giving its collected oxides very small chance to be reduced and join the iron.

Normally then, the pig iron tapped from the blast furnace will be low in oxides and sulphur, but its phosphorus content will be the same as that of the ore. Three to four per cent carbon from the fuel is dissolved in the iron. The remainder of the carbon goes off as a gaseous oxide.

**4.5. Pig Iron.** Pig iron is weak and brittle and is not used for structural purposes. Ordinarily it is poured into large ladles and taken to a cupola or an air furnace for making cast iron, or to the refining furnaces for making steel. If it cannot be used immediately it is cast into blocks or *pigs*, which may be remelted later. The different ores and various

blast furnace procedures produce many grades of pig iron, each one with a special use in the foundry or the steel mill. (See chart, Fig. 4.3.) The compositions of various pig irons are shown graphically in Fig. 4.5, where they are compared with those of the products made from each.

**4.6. Cast Iron Production.** Cast iron is used in industry because of its low cost, good casting characteristics, high compressive strength, wear resistance, and good damping qualities. The principal types are: gray, white, malleable, and various alloy irons.

*Gray Cast Iron.* Gray cast iron is made from low quality *foundry pig* which is charged (along with scrapped castings and coke) into a *cupola*, which is similar to a small blast furnace. A cupola is the best place to melt scrapped castings, so salvaged cast scrap is used to control the alloying elements in the finished cast iron.

The photomicrograph, Fig. 4.12, shows that some of the carbon in gray iron is in the graphitic form. When this iron is fractured, the exposed graphite gives the break a gray appearance, hence the name gray cast iron. Carbon combined with iron to form cementite seldom occurs in amounts greater than 0.8 per cent in these castings and the balance, 2 to 4 per cent, is in the form of graphite.

*White or Chilled Cast Iron.* White iron has its characteristic white color because it contains no graphite. All of the carbon is in the form of cementite, either free or in lamellar pearlite (see Fig. 4.13). White iron may be produced by two methods: by adjustment of composition so that the iron is white throughout, or by casting gray iron against chills to cool it rapidly and give it a white surface layer. In adjusting the composition to give iron which is white throughout, the carbon and silicon content are kept down. This adjustment is made in an air furnace where low-phosphorus pig iron and steel scrap are melted together. The air furnace heats the charge from above in a manner similar to the open hearth (see Fig. 4.6), and is used because the entire charge can be dumped in, heated, and carefully controlled. Cupola furnaces alone are sometimes used for making low quality white castings, but better castings can be made by "duplexing" or "triplexing" processes which combine the cupola, air furnace, Bessemer converter and/or electric furnace. (See Fig. 4.3.)

*Malleable Cast Iron.* Most of the white iron castings made are converted into malleable iron castings. To do this, an all-white casting is annealed in such a way that all of the carbon, which was in the form of cementite (Fig. 4.13), agglomerates and forms "rosettes" of pure temper carbon scattered in a matrix of almost pure iron (Fig. 4.14). The annealing process is one of slow heating, long holding at temperature and slow cooling, requiring from 25 hr (for small sections) to 6 days.

## IRON AND STEEL

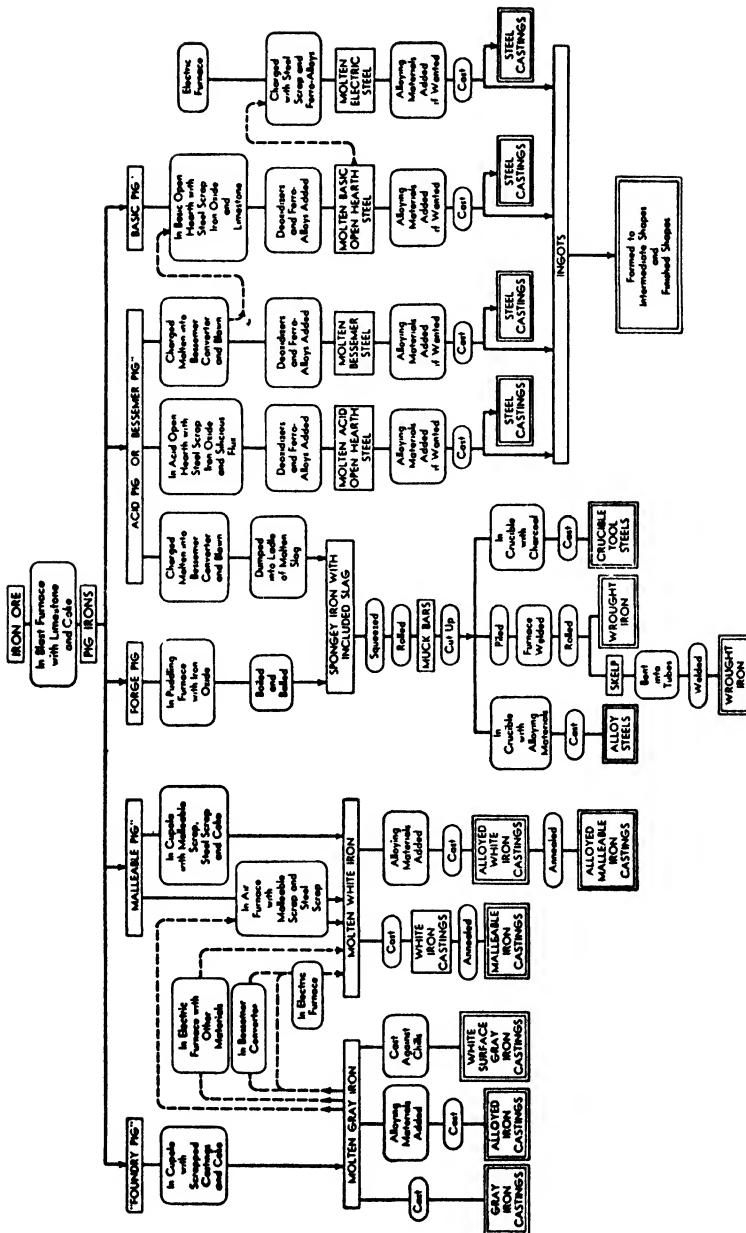


FIG. 4.3. Diagram indicating typical foundry and mill applications for different grades of pig iron.  
Finished products are shown in double outline.

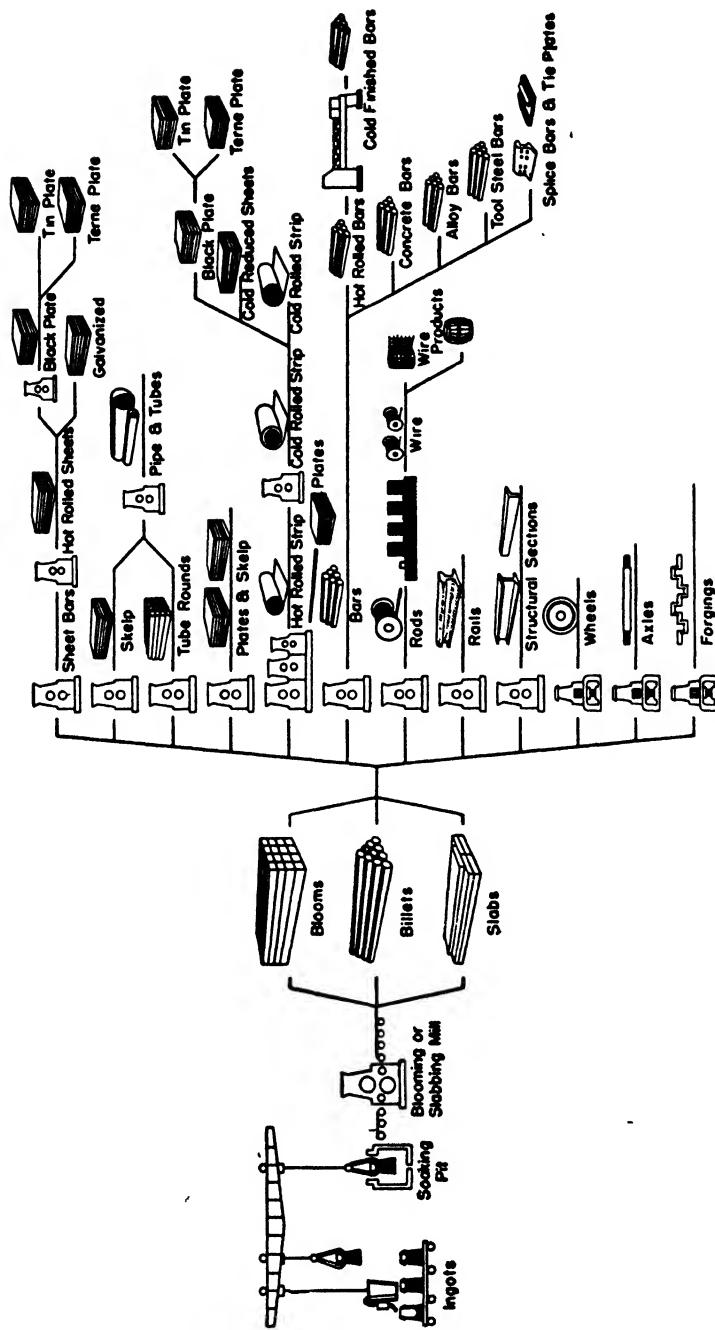


FIG. 4.4. Typical foundry and mill products and methods used to shape them from ingots. (*Adapted from Victory Bulletin, Vol. 3, No. 52.*)

## IRON AND STEEL

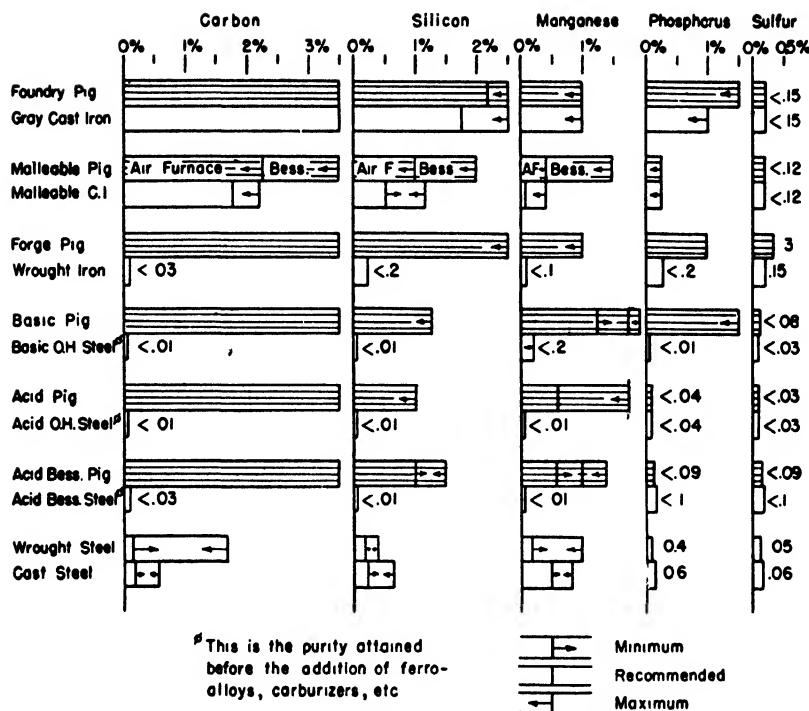


FIG. 4.5. Compositions of various pig irons and the cast irons and steels derived from them. Shaded bars represent pig irons. Unshaded bars represent refined product.

**Alloyed Cast Iron.** Many foundries have unsuccessfully attempted to produce alloyed cast irons in cupola furnaces, but the difficulties met in attempting to add alloying elements in the cupola are almost insurmountable. The alloying compounds may be added to the cupola charge, but very often do not melt evenly and so give castings of non-uniform composition. If the alloys are added to the pouring ladle after the molten iron is drawn from the furnace, the ladle iron must be very hot to overcome the chilling effect of the alloy, and even then the mixture is apt to be nonuniform.

Many of the disadvantages of the cupola are overcome by use of the "batch process" in an air furnace or an electric furnace. In these furnaces it is possible to control the composition, since the charge is melted all at once instead of continuously as in the cupola. Probably about 15 or 20 per cent of the cast iron being produced now is alloyed, and many foundries make a specialty of this type of casting.

**4.7. Wrought Iron Production.** Wrought iron was the first tough, ductile material used in structural work, but it is used very little today. This is because many steels are superior in almost every way to wrought iron, and are much less expensive. Wrought iron remains superior for some applications, however, where corrosion and severe fatiguing conditions exist. A good grade of pig iron called *forge pig* containing less than 1.75 per cent silicon and less than 1 per cent phosphorus is the material used (see Figs. 4.3 and 4.5) and is refined into wrought iron either by "puddling" or by the Aston process.

*Puddling Process.* The puddling process was invented about 1780 and is still in use. In it, a charge of forge pig is placed in the saucer-shaped hearth of a puddling furnace and is melted by a flame from above similar to that employed in the open hearth furnace (see Fig. 4.6). As the iron melts, iron oxide is added to oxidize the Mn and Si impurities (see Fig. 4.2) and thus starts the formation of a slag. When this is completed, the carbon begins to oxidize and burns from the surface of the metal. As the carbon is eliminated, the melting point of the mix is raised and solid iron starts to precipitate. The puddler starts stirring the mix, thus agglomerating the precipitated iron into a ball which he removes, dripping with slag, from the furnace. The ball is taken to a *squeezer*, where much of the slag is squeezed out, and then is rolled into a bar (called a *muck bar*), thereby removing more slag. This muck bar is cut into short lengths and is the finished product, wrought iron. It is very pure, except for 1 to 2 per cent slag in the form of streamers scattered throughout the ferrite matrix (see Fig. 4.15). If the wrought iron is to be used for other than crucible steel, several muck bars are laid side by side, furnace-welded, and rerolled several times. This refines the grain, eliminates a little more slag, and provides larger billets for structural use.

Because a large amount of hand labor is required in the puddling process, it is expensive and is little used today.

*Aston Process.* Many of the difficulties encountered in the production of wrought iron in the puddling furnace were overcome in 1930 when Aston developed a method requiring no puddling. In his process the pig iron is purified in a Bessemer converter (see Fig. 4.7) and then dumped into a ladle of molten slag. The temperature of the slag is several hundred degrees lower than that of the iron, and a violent reaction takes place, mixing the slag through the iron. The resulting mass resembles the puddler's "puddle ball," and subsequent squeezing, rolling, piling, furnace-welding, and rerolling yield a wrought iron which is very similar to that produced in the puddling process. The iron produced by the Aston process is more uniform, never containing large slag

inclusions or streaks of pure carbon such as sometimes appear in puddled iron.

**4.8. Commercially Pure Iron.** Commercially pure iron is sometimes used for its good ductility and resistance to corrosion. It has been produced by many methods, but few have been commercially exploited. One process which has been successful takes place in the basic open hearth furnace (described below). The composition of the charge and furnace lining are carefully chosen, and the process is longer and more accurately controlled than is open hearth steel making. The resulting iron is known as *ingot iron* (or by its trade name, *Armco Iron*) and contains about 0.2 per cent total impurities. It is used in wire fencing, culverts, flumes, gutters, troughs, home furnaces, or for other applications which require moderate resistance to rusting.

A commercially pure iron is also made by electrolytic deposition. Its total impurities may be considerably less than 0.1 per cent, so it is very ductile and can be rolled or hammered, like gold, to very thin sheets. Since it is expensive, the commercial production is small.

**4.9. Steel Production.** Steel can now be manufactured in such great quantity at small expense and with so many varieties of desirable physical properties that it has largely replaced wrought iron. In addition, many parts formerly made of cast iron are now either cast or fabricated from steel.

Steel production in the United States during 1942 as reported by the American Iron and Steel Institute was:

	<i>Net Tons</i>
Open hearth steel (about 95 per cent basic open hearth)	76,564,593
Bessemer steel (acid)	5,593,248
Electric furnace steel	3,974,368
Total	86,132,209

***Open Hearth Processes.*** In 1856 Siemens patented a furnace destined to become the largest producer of steel, the open hearth furnace. The outstanding feature of this furnace is the intense heat obtainable by its regenerative process (see Fig. 4.6). The flame burns above a shallow vessel containing the charge of pig iron, steel scrap, iron ore, and flux. As the charge melts, the flux forms a slag which is raked off into slag pockets at the side of the furnace. Fig. 4.5 indicates graphically the purification which takes place in the furnace. After this refining, re-carburizers and ferro-alloys (high alloy content iron alloys) are added to bring the steel to the desired composition, because after refining, the carbon, silicon, and manganese contents may be lower than desired.

This apparently wasteful procedure of eliminating the impurities, and then adding them again in the desired amounts is in reality more efficient than trying to decrease them to just the right amounts.

At the high temperatures encountered in the furnace, the furnace lining becomes chemically active. Silica becomes an acid, while the other common lining materials, calcium and magnesium oxides, become

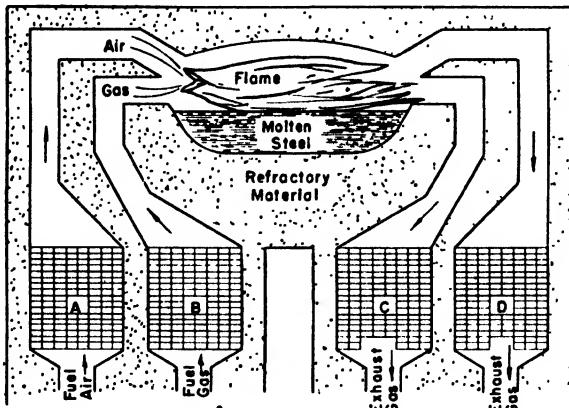


FIG. 4.6. Elementary cross-section of the open hearth furnace. *A, B, C, and D* are checkerworks for storing heat. When the flame is in the direction shown, *C* and *D* are being heated by the burned gases. Every 15 minutes the direction is reversed; i.e., air and gas will enter through *C* and *D*, which are hot; the flame will burn from the right side, and *A* and *B* will be heated by the burned gases. As time goes on, the system becomes hotter and the flame gradually grows more intense. This is known as the regenerative principle.

bases. The slag is also chemically active, but its acidity or alkalinity can be controlled by selection of flux. If the lining is basic, the flux must also be basic, or the slag would destroy the lining; the converse is of course true. The basic slag of a *basic open hearth* furnace will remove most of the silicon, manganese, and phosphorus in the iron, as well as some of the sulphur, but the *acid open hearth* will remove only the silicon and manganese (phosphorus and sulphur remain). The basic furnace can refine dirtier pig iron and is by far the more popular, even though the lining is more expensive than the acid lining.

Each heat (complete refining cycle) requires about 10 hr, and furnaces producing as much as 250 tons of iron per heat are in use.

*Bessemer Converter Processes.* About the same time that the open hearth furnace was invented, Henry Bessemer developed this refining process which requires no fuel. Instead, the heat is supplied by the oxidation of the impurities in the pig iron. Fig. 4.2 shows that the

oxidation of calcium would produce the most heat, silicon less, and so on. Silicon and manganese occur in pig iron in sufficient quantities to increase the temperature of the molten iron when they are oxidized by even a blast of cold air. The Bessemer process takes advantage of this by blowing cold air in at the bottom of a pear-shaped vessel (see Fig. 4.7) which has just been filled with molten pig iron from a blast furnace. As the air bubbles through the iron, Si and Mn are oxidized to form a slag and the temperature gradually rises. Carbon is then oxidized and burns with a long flame from the mouth of the converter. After the carbon "blow," recarburizers and ferro-alloys are added and the charge is dumped and cast into ingots.

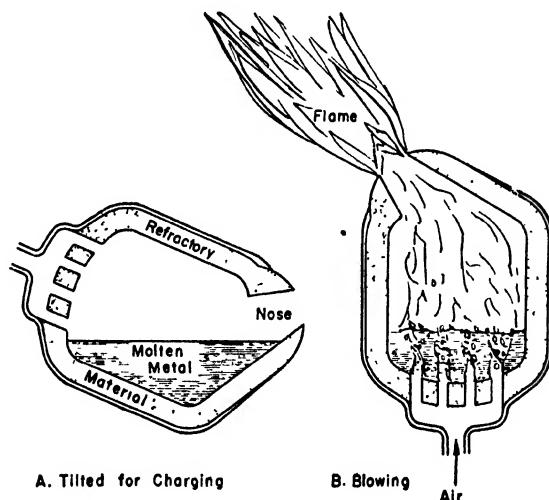


FIG. 4.7. Elementary cross-section of the Bessemer converter. Molten pig from the blast furnace is charged in the nose. Air is turned on and the converter is tilted upright as in B. Blowing continues for 10 or 12 minutes. The converter is then tilted in the opposite direction and emptied.

In the *acid Bessemer* process, most of the silicon and manganese are eliminated by the slag, but all of the phosphorus and sulphur remain. Therefore, phosphorus and sulphur in the pig must be less than the maximum allowable in the steel. *Basic Bessemer* is not used in the United States because its principal raw material, low-silicon high-phosphorus pig iron, is uncommon in this country.

Since silicon supplies most of the heat in the Bessemer process, the quantity of silicon in the pig iron is held nearly constant so that the steels produced will be as uniform as possible. A Bessemer blow takes only

10 or 12 min and produces 25 tons of steel, so one Bessemer converter can keep about two blast furnaces busy.

This refining process is rapid and simple, so pig iron is sometimes refined in a Bessemer before being charged into the basic open hearth. The silicon is eliminated in the acid Bessemer where it does no harm, and the carbon is reduced in the Bessemer where the process is rapid. Consequently, the length of heating in the hearth is shortened, and since the sulphur and phosphorus are reduced in the hearth, a very clean steel is produced. This method is known as *duplexing*.

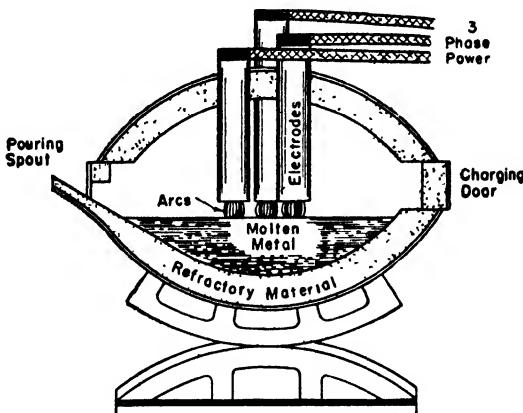


FIG. 4.8. Elementary cross-section of three-phase electric arc furnace. Electricity flows through the metal because the total resistance of this path is smallest. Mechanisms on the electrodes automatically regulate the length of the arcs.

*Electric Furnace Processes.* The development of electric furnaces has been a boon to the steel industry because higher and more accurately controlled temperatures are obtainable, and because the charge may be exposed to an atmosphere which will not contaminate the metal. The high cost of electric power is the limiting factor and accounts for electric furnaces being used only for high quality steel production, usually tool steels and alloy steels. Two types of furnaces are in general use for melting and smelting: the arc furnace and the induction furnace.

Some arc furnaces have been built for single-phase and d-c operation in which the molten metal is one electrode and a carbon stick is the other, but most furnaces are of the three-phase type shown in Fig. 4.8. In these the metal is heated by current flowing through it and by radiated heat from the arcs. The molten metal is not an electrode; the current flows through this metal only because the resistance of the iron path is much less than the resistance of the air between the electrodes. Suit-

able regulators keep the electrodes at the right distance above the molten metal.

In the induction furnace the metal is also heated by a current within itself, but the entire circuit of the current is within the metallic charge, being induced by means of a strong magnetic field. Fig. 4.9 shows a simple induction furnace in which the magnetic field is set up by a coil of wire around the crucible containing the metal. The higher the frequency of the alternating current in this coil (voltage remaining con-

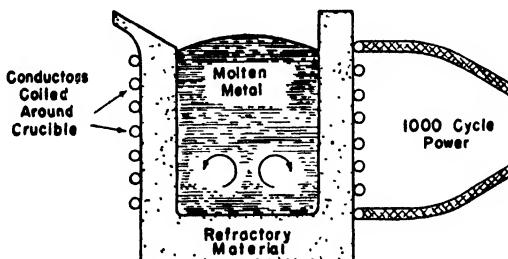


FIG. 4.9. Elementary cross-section of induction furnace. Current in the coil induces currents in the metal (as shown by arrows), causing heat. Conductors are water cooled.

stant), the better the heating effect. Frequencies of about 1000 cycles are in common use because they are readily obtainable, whereas higher frequencies require expensive generators. The heating effect of the induction furnace is analogous to the heat generated in the secondary of a transformer. The coil on the furnace is usually a copper tube and water is circulated through it to keep it cool.

The electric furnaces can produce steel of almost any desired purity and composition because various fluxes may be used and the operator can take samples of the melt from time to time, analyze them, and add whatever is needed to bring the steel to the desired composition.

*Crucible Process.* All steels were made in crucibles before the invention of the open hearth and Bessemer. The crucible is a ceramic cup or vessel in which are placed materials in the right amounts to give steel of the proper final composition. The crucible is then heated until the charge is molten and ready to pour into ingots. Except for removal of gases and nonmetallic inclusions, there is little refining action in the crucible, and the process is therefore not used extensively.

**4.10. The Casting of Steel.** The molten steel coming from the refining furnaces may either be cast into the desired shape in which it will be used or it may be cast into an *ingot* and then rolled, forged, hammered, pressed, or machined into the desired shape. Castings will

be discussed in Chapter XII; ingots are discussed below. Most steel mills are arranged in such a way that the refining furnaces take molten pig from the blast furnaces, refine it, and cast it into ingots which are kept hot until ready for the blooming or rolling mill. In this way the iron is not cold from the time it enters the blast furnace as iron ore until it is a finished steel shape.

After steel has been refined in an open hearth or Bessemer, it is apt to contain oxygen in the undesirable forms of iron oxide and dissolved gas. The carburizer that is added to bring the carbon content of the steel up to the desired amount tends to deoxidize the iron, forming CO<sub>2</sub>, which bubbles up and causes "boiling" in the ingot before the steel solidifies. As the steel solidifies, some of the gas becomes trapped and forms *blowholes* or voids in the ingot. Steel cast in this way has a characteristic solid rim of metal next to the mold, and is called *rimmed steel*. It has a smooth surface, and products rolled from these ingots (strip, sheet, plate) have an excellent surface finish.

Blowholes deep in an ingot may cause no harm if the ingot is to be rolled because the rolling takes place at welding heat, and the holes are effectively welded together. Blowholes near the surface, however, may break out in cracks which no amount of mechanical work will eliminate. To minimize the occurrence of these blowholes, steel may be *killed* by adding other deoxidizing materials to the ladle just before casting. Aluminum, vanadium, silicon, and manganese effectively deoxidize iron and carbon (see Fig. 4.2) and are most commonly used.

Steel ingots are cast in a cast iron mold. The molten metal is introduced into the mold either from the top or from the bottom. The liquid next to the mold walls solidifies first, and the solidification progresses inward. There are definite directional tendencies in the grain growth, as explained in Chapters I and II; and in addition to coring within the individual grains, the grains differ somewhat in both composition and structure from the surface to the center of the ingot. The contraction of the metal during cooling causes a cavity or pipe at the top of the ingot which extends downward at the center. Usually the ingots are provided with a "hot top" or small reservoir of metal which feeds the ingot as it solidifies and thus prevents a large pipe from forming.

Segregation also takes place as the ingots freeze. Dissolved elements, such as carbon, phosphorus, and sulphur, are less soluble in the solid iron than in the molten iron, and they tend to migrate from the solidifying steel into the neighboring molten steel. The molten steel therefore becomes higher and higher in impurities and often the metal near the pipe is very dirty because it has solidified last. Control of segregation is difficult, but it is generally true that the more impure a steel is, the

greater the tendency it has to segregate. The carbon tool steels and spring steels must be cast in small ingots to lessen the chance for carbon migration before the whole mass solidifies. Some alloy steels are also handled in this way.

**4.11. The Mechanical Treatment of Steel.** The purpose of mechanically working steel is to change its dimensions, properties, or surface

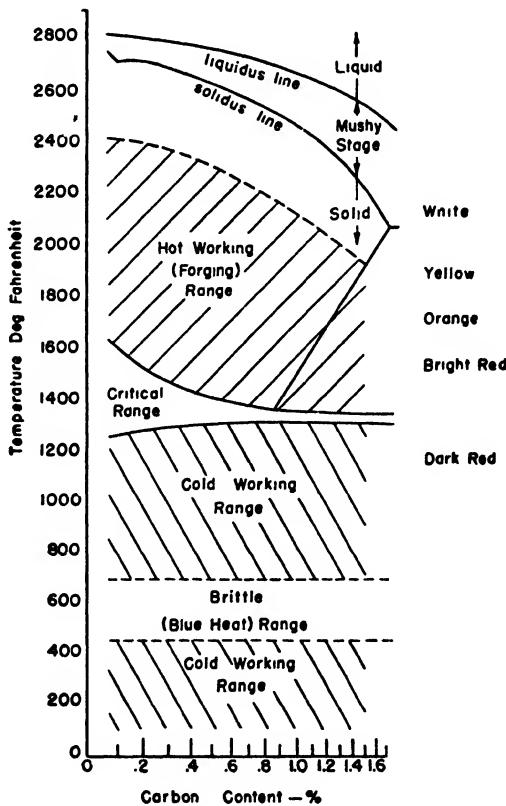


FIG. 4.10. Working temperature ranges of steel.

condition. The ingots are usually kept hot in *soaking pits* until it is convenient to hot work them. The top end of the ingot, containing most of the pipe and segregated impurities, is cut off and scrapped; the sound part of the ingot is rolled down to a *bloom*. The bloom, which has a cross-sectional area greater than 36 sq in., may then be rolled down to a *billet*, which has a cross-sectional area between  $1\frac{1}{2}$  and 36 sq in., or to a *slab*, which is at least  $1\frac{1}{2}$  in. thick, has a width more than twice its

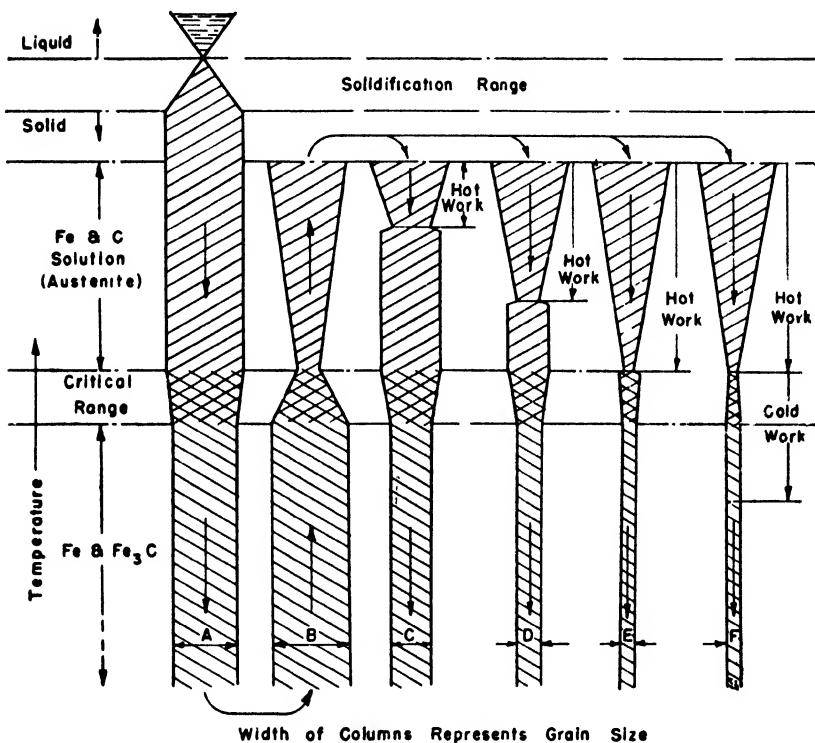


FIG. 4.11. Effect of mechanical working on grain size of steel.

- A. Liquid steel cooled to room temperature. (Grains form upon solidification, re-form to smaller grains in critical range.)
- B. Steel heated to high temperature. (Reduction of grain size in critical range and then growth above this range.)
- C. Small amount of hot working. (Grains are refined, but grow again to size characteristic of temperature at which hot work is stopped.)
- D. Larger amount of hot working. (Grains have less chance to grow.)
- E. Hot working to critical temperature. (Grains cannot grow; maximum refinement is attained.)
- F. Working below critical. (The cold work causes no further refinement; only distortion of grains results.)

thickness, and usually has an area not less than 16 sq in.<sup>1</sup> These various forms may then be reduced to any of the many finished shapes shown in Fig. 4.4. Most of the shaping is done by hot working in the forging range (see Fig. 4.10).

Fig. 4.11 demonstrates grain growth and refinement in a steel which is

<sup>1</sup> American Iron and Steel Institute, Steel Products Manual, Section 2, May, 1942. These distinctions are in general use but are not universal.

solidified from the liquid state, heated again to a forging temperature, and then worked for a certain interval. The figure clearly indicates that the best grain refinement obtained by mechanical treatment takes place if the hot working is continued until the steel has cooled to its critical range.

The hot and cold working operations used in industry are discussed in Chapters XIV and XV.

**4.12. Cast Iron.** When cast iron solidifies, the last liquid to freeze is of the eutectic composition (4.3 C). If no other alloying element is present, the quantity of carbon must be at least 1.7 per cent for the eutectic transformation to occur (see Fig. 2.11). If the percentage is

lower, there will be no final solidification of eutectic liquid, and the solid will not be cast iron. Impurities and alloys, however, change this value considerably; for instance, 2 per cent silicon lowers the possible carbon limit to 1.1 per cent.

The four kinds of cast iron developed by the metallurgist are gray (ferritic), austenitic gray, white, and malleable.

*Gray Cast Iron.* In gray cast iron, the iron is in the form of ferrite and the carbon appears to some extent as free graphite. Although it is possible to produce this iron with all the carbon as free graphite flakes, this is seldom desirable, so in most castings an appreciable amount of the carbon is in the form of iron carbide,  $\text{Fe}_3\text{C}$  (see Fig. 4.12). The

FIG. 4.12. Photomicrograph of gray cast iron  $\times 1000$ . White areas are ferrite, mottled areas pearlite, and black areas graphite.

eutectoid percentage of this carbide appears in lamellar pearlite, and the amount of combined carbon in excess of that percentage appears as free massive grains. Thus a complete series of gray cast irons is possible ranging from those with all the carbon in graphitic form to those with a good share of the carbon in combined form. Since the carbides harden and strengthen the iron, the variation in properties over this range of irons is very great; completely graphitic gray iron is a soft, readily machinable metal, whereas irons with a high proportion of the carbon occurring as carbide are hard, brittle, unmachinable, and have good wear resistance.



The relative amount of free and combined carbon is controlled by variations in composition, melting practice, and casting practice. The most potent single factor is the presence of silicon, which promotes the decomposition of cementite into free iron and graphite. Another important variable is the cooling rate of the iron in the mold, because slow cooling aids the formation of graphite and rapid cooling aids the formation of cementite; in fact, iron which would be gray throughout if sand cast may be given a white surface by casting it against chills, which cool the surface rapidly. Ordinarily it is desired that the amount of combined carbon in gray cast iron be less than the eutectoid percentage, and for this reason the silicon content is kept up to about 2 per cent and the metal is cooled without chilling. A close-grained iron low in total carbon is generally the strongest, toughest, and best finishing type of cast iron.

Sulphur has the opposite effect from silicon; it stabilizes the carbide and thereby tends to "chill" the iron. This action is prevented if manganese is present in sufficient amounts to combine with all of the sulphur to form manganese sulphide. Phosphorus in cast iron occurs almost entirely combined with iron and carbon to form a eutectic called steadite, which does not materially decrease the strength or increase the brittleness the way phosphorus would if free within the iron.

The principal reasons for alloying cast iron are to increase its strength and to improve its corrosion resistance. Alloying is a process requiring special melting practice; so alloys are added to good irons to make them better, never to poor irons to make them good.

**NICKEL** (up to 5 per cent). Nickel in amounts up to 5 per cent is added to cast iron primarily for its effect on machinability; it may be made either to increase the hardness and strength without appreciably decreasing the machinability or to improve machinability without decreasing hardness and strength. The nickel also promotes corrosion resistance and uniformity of properties throughout variations in casting thickness.

**CHROMIUM** (up to 3 per cent). Chromium has the opposite effect from silicon and nickel; it inhibits the formation of graphite, promotes the formation of carbides, and in addition increases the corrosion resistance. Increases in chromium content therefore harden the iron by increasing the percentage of combined carbon.

**NICKEL-CHROMIUM** (in 3-to-1 ratio, up to 4 per cent total). These elements are added in such proportions that their graphite- and carbide-forming tendencies neutralize each other, and this results in iron with improved grain refinement, hardness, and strength, and with no impairment of the machinability.

**MOLYBDENUM** (up to 1.5 per cent). Molybdenum is the most effective alloying element for improving strength; wear resistance is also increased, with a consequent decrease in machinability. Molybdenum improves the uniformity of structure in heavy sections by slowing up graphitization and retarding the critical transformation.

**VANADIUM** (up to 0.5 per cent). Vanadium is a very powerful carbide-former and increases the strength and hardness of cast iron considerably even in the small amount used.

*Austenitic Gray Cast Iron.* If iron is alloyed in such a way that the critical transformation temperature is lowered below room temperature, then the iron will remain in the form of austenite ( $\gamma$ -iron) rather than transforming to ferrite ( $\alpha$ -iron) as it cools to room temperature.

Austenitic cast iron, which bears the same relationship to ferritic cast iron that stainless steel bears to carbon steel, has excellent corrosion and erosion resistance and good wearing qualities, strength, and hardness.

**NICKEL** (10 to 20 per cent). Nickel is the only alloying element known which alone causes iron to remain in austenitic form (at room temperature) without causing its carbide content to increase.

*White Cast Iron.* White cast iron, which is an iron containing almost no free graphite (Fig. 4.13), is a very hard, brittle, wear-resistant substance obtainable by composition adjustment or chill casting as explained before. If the silicon is kept below 1 per cent and the carbon is adjusted to about 2 per cent in common cast iron, a white iron of about 400 Brinell will usually result.

**CHROMIUM** (over 3 per cent). In amounts greater than 3 per cent, chromium usually prevents the formation of graphite in cast iron. The resultant iron not only has the common properties of other white irons, but also has better high-temperature strength, growth resistance, and corrosion resistance.

**NICKEL-CHROMIUM** (4.5 per cent Ni, 1.5 per cent Cr). This small addition of alloying materials doubles the strength and significantly increases the toughness of white castings. It is used when an extremely hard (700 Brinell), tough, and strong material is desired.

*Malleable Cast Iron.* Malleable castings are produced by the annealing of white castings. In this process some or all of the carbon (which is in the combined form in the white casting) is changed into fine graphite powder which agglomerates and forms *rosettes* scattered throughout the matrix. (See Fig. 4.14.) This matrix may have one of several forms depending on the heating cycle to which the white casting was subjected. Castings up to 2 in. in thickness may be completely malleabilized, and even up to 4 in. if the decrease in ductility at the center caused by uneven

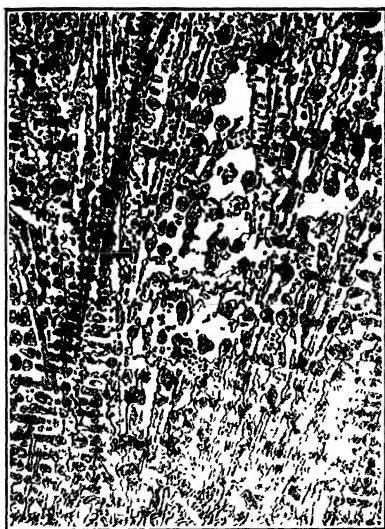


FIG. 4.13. Photomicrograph of white cast iron  $\times 250$ . White areas are cementite ( $\text{Fe}_3\text{C}$ ), and mottled areas are pearlite.

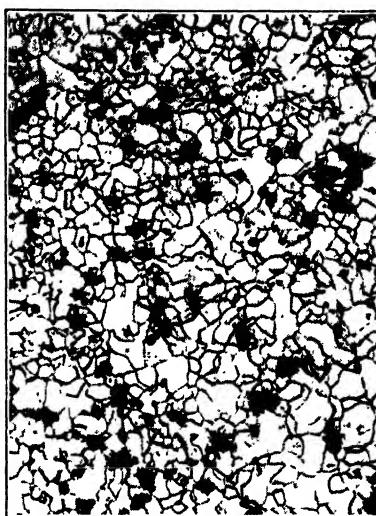


FIG. 4.14. Photomicrograph of malleable cast iron  $\times 125$ . Black "rosettes" of temper graphite in a matrix of pure iron.



FIG. 4.15. Photomicrograph of wrought iron  $\times 100$ . Black areas are slag inclusions in the nearly pure iron.

heating is not objectionable. Malleable castings have excellent strength, ductility, impact and corrosion resistance, and molding and machining qualities, compared with other cast irons.

The usual cost of malleable cast iron will be between that of gray iron and softer steel. Its handicap is the relatively long time for delivery, because of the time required for the annealing treatment after casting.

**4.13. Steels.** Many varieties of steel are produced, but the engineer usually does not need an exact knowledge of every one of them. He should, however, be acquainted with the different types of plain carbon steels and the effects of various alloying elements upon them. This overall picture will enable him to make proper use of the large amount of available test data and specifications when he must select a steel for a particular application.

Plain carbon steels, which constitute about four-fifths of the steel produced, will be discussed first.

**Plain Carbon Steels.** These steels are usually thought of as being composed of iron in the form of ferrite and of less than 1.7 per cent of carbon in the form of iron carbide (cementite). These steels may also contain small amounts (0.5 per cent maximum) of deoxidizing agents such as magnesium, silicon, and aluminum. If other elements are added to alter the properties, the steel is called an *alloy steel*.

Plain carbon steels are cheaper than the alloy steels and consequently are used wherever their properties are adequate. They range from very soft to very hard, and are suitable for a large proportion of industry's needs. Table 4.1 shows several types of steel, the first five of which are plain carbon steel.

In general, the low carbon steels with as much as 0.25 per cent carbon are tough, ductile, and easily formed and welded. They are used in tin-plated cans, wire, wire products such as fencing, nails, and wood screws, and all kinds of cold-forged parts which do not need high strength. Although the low carbon steels are not hard, some grades are easily surface hardened by case carburizing.

The strength and hardenability generally increase with carbon content. Medium carbon steel (0.40 C) is stronger and more hardenable than low carbon steel, and is not so easily cold formed. It is often used (sometimes with alloying elements or higher carbon content) for forgings which require moderately high strength, such as shafts, axles, gears, crank pins, and any other parts subject to shock.

Steel with carbon content of 0.75 per cent or more is used for hammers, wrenches, springs, and any other devices which require still higher hardness and strength. Very hard tools, such as metal saws, are made of steel with as much as 1.50 per cent carbon, and compositions in the whole

TABLE 4.1. STEELS REPRESENTATIVE OF TYPES USED IN THE ELECTRICAL INDUSTRY

Composition							Characteristics			Applications	
C	Mn	P	S	Si	Cr	Mo	Ni	Misc.			
0.10	0.40	0.04 <sup>1</sup>	0.05 <sup>1</sup>						Tough, ductile, weldable, low strength.	Rivets, hot and cold headed parts, wire products.	
0.20	0.50	0.04 <sup>1</sup>	0.05 <sup>1</sup>	0.20					Tough, weldable, easily formed, may be carburized.	Small forgings, boiler plate, structural shapes, case hardened machine parts.	
0.40	0.75	0.045 <sup>1</sup>	0.055 <sup>1</sup>						Moderate strength, may be formed.	Large forgings, shafting, axles, gears.	
0.75	0.40	0.05 <sup>1</sup>	0.05 <sup>1</sup>						Good hardenability, high strength.	Springs, wood cutting tools, hammers, wrenches.	
1.0	0.40	0.04 <sup>1</sup>	0.05 <sup>1</sup>						Greater hardenability, high strength.	Metal cutting tools, dies, punches, saws.	
Plain Carbon Steels							Characteristics			Applications	
0.10	0.75	0.10	0.12							Screw machine parts.	
0.15	1.50	0.045 <sup>1</sup>	0.10								
0.40	0.70	0.04 <sup>1</sup>	0.04 <sup>1</sup>	0.25	0.70	0.35	1.80		Carburizing qualities.	Small shafts, forgings, screw machine parts.	
0.40	0.80	0.04 <sup>1</sup>	0.04 <sup>1</sup>	0.25					Increased strength.	Heat treated machine parts, axles, gears.	
0.40	0.35	0.50	0.045 <sup>1</sup>	0.04 <sup>1</sup>	0.30 <sup>1</sup>	1.25	0.20	0.50 <sup>1</sup>	High strength toughness, hardenability.	Bolts, shafts, forgings.	
0.50	0.80	0.025 <sup>1</sup>	0.025 <sup>1</sup>	0.25	1.0	0.25			Nitriding steel.	Case hardened shafts, pins, etc.	
0.20	0.75 <sup>1</sup>	0.035 <sup>1</sup>	0.045 <sup>1</sup>	0.045 <sup>1</sup>	0.25		0.50		High strength, toughness, hardenability.	Strong, tough bolts, bushings, shafts.	
0.85	0.60			0.25	4.0	5.0			Strength, creep resistance.	High temperature bolts, structural parts.	
0.10	1.25 <sup>1</sup>	0.03 <sup>1</sup>	0.03 <sup>1</sup>	0.75	18.0	8.0			Oil hardening, nondeforming, red hardness.	High speed cutting tools, dies, intricate hardened parts.	
									Rust resisting, high strength, creep resisting.	Transportation and food-handling equipment, high temperature machine parts.	

<sup>1</sup> Maximum allowable quantity.

range of steels with 0.75 to 1.50 carbon are used for dies, punches, chisels, drills, and other hard, strong parts.

Although carbon is important in determining the characteristics of a steel, the impurities left by the refining operation may also be important in some applications. Phosphorus and sulphur, for instance, reduce the ductility, malleability, and resistance to shock and fatigue. Bessemer steel, which is often high in phosphorus and sulphur, is therefore seldom used when such properties are needed. But where loading is not heavy or rapidly repeated, Bessemer steel is satisfactory. Screw stock, sheets, tin plate, tubing, pipe, concrete reinforcing and light-weight rail are very commonly made of Bessemer steel. Open hearth steel has higher purity (see Fig. 4.5) and is preferred for heavy rails, structural shapes for buildings and bridges, boiler plate, rivets, springs, shafts, axles, gears, and high carbon tools. The electric furnace is also used to produce plain carbon steels, but its greatest application is in the manufacture of alloy steels.

*Alloy Steels.* There are hundreds of varieties of alloy steels, but they are used only where they provide one or more clear-cut advantages over any available plain carbon steel. The alloying elements do not make a steel better in every respect; they tend to improve some characteristics at the expense of others. The free machining steels, for instance (high sulphur steels in Table 4.1), sacrifice ductility, malleability, and resistance to impact and vibration.

Table 4.1 shows a number of other alloy steels. The alloying elements are usually added for the reasons shown in Table 4.2. Silicon, for example, is added for improved strength but at a sacrifice of cold workability. The silicon steels are used for structural members in bridges and buildings where this extra strength can be used effectively. They also have special magnetic properties, and various grades are used in motors, transformers, and other magnetic devices. For a more complete discussion, see Chapter VIII.

Chromium, nickel, manganese, and molybdenum improve hardenability and strength. A development brought about to conserve these alloys is the use of minute quantities of boron. The boron is added to the melt at the ladle as a ferro-alloy, and the very small amounts needed cause increases in hardenability equivalent to that of much larger percentages of the other alloying elements; e.g., 0.002 per cent boron is equivalent to 1.5 per cent nickel or 0.25 per cent molybdenum. The cost of the ferro-alloys is high, but the small quantities used plus the beneficial effect of the other alloying elements they contain make their use practicable.

In large quantities, chromium and nickel (18 to 25 Cr, 8 to 20 Ni)

TABLE 4.2. EFFECTS OF ALLOYING ELEMENTS<sup>1</sup> UPON PROPERTIES OF STEEL

	Carbon 0.10-0.30	Carbon 0.31- eutectoid	Mn 0.25-2.00	P 0.0-0.15	S 0.0-0.3	Si 0.0-2.0	Cr 0.0-1.1	Ni 0.0-5.0	Mo 0.0-7.50	V 0.0-0.25	Cu 0.0-1.1
Effect of single alloying element upon low carbon steel (0.1-0.3 C)											
Hot working	+2P	-7P	+7S	0	-10S	-5P	0	-6P	-3P	0	-10S
Cold drawing	-4P	-10P	-10P	-10P	-10S	-10S	-10S	-10S	-10P	x	-10P
Cold bending	-2L	-10P	+2I	-10L	-7P	-6P	-10P	+5S	+3P	+2P	
Machinability <sup>2</sup>	+2P	-2P	-6P	+6P	+10P	-2P	-2P	-10P	-5P	0	x
Weldability	-2L	-10P	-10L	-7L	-3P	-5L	-10L	-10L	+1P	-4L	
Hardenability (depth)	+1P	+2P	+10P	+3P	-2P	+2S	+7S	+10L	+7S	+5I	xx
Strength <sup>2</sup>	+4P	+10P	+5P	+5P	-2P	+7P	+5P	+5P	+5P	0	+1P
Creep resistance	+2I	-3P	0	0	0	0	+1P	+10P	? <sup>3</sup>	?	
Toughness <sup>2</sup>	-3P	-8P	+2I	-8P	-6P	-2P	-8P	+10P	+3S	+2P	+1L
Low temp. toughness <sup>2</sup>	-3P	-10P	+2I	-10S	-6P	-1P	-10P	+10S	+3S	x	
Corrosion resistance	-3P	-6P	0	+10P	-10P	+2P	0	+6L	+2P	0	+10S
Wear resistance <sup>3</sup>	0	+10P	+6P	+1P	0	+2P	+8P	+3L	+5P	+2P	xx

## Key

Number indicates relative magnitude of effect.

+ Improvement in property.

- Reduction in property.

P Effect is proportional to quantity of alloying agent.

xx Probably positive.

S Small quantities most effective.

L Large quantities most effective.

I Intermediate quantities most effective.

x Probably negative.

<sup>1</sup> From data by Mr. John Mitchell, in "Contributions to the Metallurgy of Steel," Am. Iron & Steel Inst., by permission of the author and publisher.

<sup>2</sup> As rolled.<sup>3</sup> Fully hardened.

improve corrosion and creep resistance, and give a group of corrosion-resisting alloys known as the "stainless steels" (see Chapter VII). They are expensive, but have been used in increasing quantities during the last few years. Such variations as free machining and cutlery grades of stainless steel are available.

A steel containing aluminum (Table 4.1) may be case hardened by nitriding to a much greater surface hardness than could be obtained by carburizing.

Tungsten and molybdenum give some steels ability to retain their hardness at red heat, and so they are used in high-speed cutting tools. The high-speed steel, shown in Table 4.1 is strong when hot, and is also nondeforming, that is, the finish machining on a die or intricate tool may be done while the tool is soft and the shape will be accurately retained by the part through the hardening process. Such steels are, of course, expensive compared with the plain carbon steels, and only small quantities (by weight) are used.

**4.14. Conclusion.** In normal times, there are hundreds of varieties of plain carbon and alloy steels used commercially. These various grades are usually distinguished by chemical and physical specifications and designations, which follow comprehensive systems made up by such groups as the American Iron and Steel Institute, the American Society for Testing Materials, and the Society of Automotive Engineers. In addition, many large consumers have their own specification systems, for steels and other materials as well.

During the war, a great effort has been made to standardize on a relatively small number of steels, known as the "National Emergency Steels." Their compositions have been adapted from the American Iron and Steel Institute specifications to minimize the number of different compositions which must be supplied, and to conserve those alloying elements whose supply is critical.

In view of the present usage of emergency specifications and the possibility that these will be changed periodically, no system of specifications or designations has been given in this chapter. Instead the various grades of iron, plain carbon steel, and alloy steel have been discussed in a general way and the purpose has been to give an over-all picture of the production and application of these ferrous alloys. This picture should help the designer to make the most effective use of the current buyer's and manufacturer's specifications with which he will work.

Although the specific compositions and physical properties of the alloys and their adaptability to various manufacturing processes are left to current specifications, the processes most often used with each general

class of alloy were briefly mentioned. They will be discussed more completely in later chapters on processing.

### REVIEW QUESTIONS

1. Name the three principal constituents of the blast furnace charge and the function of each. In what form is each when it leaves the furnace?
2. What determines the temperature at which the various blast furnace reactions take place?
3. Carbon appears in different forms in the various kinds of cast iron. What are the forms and how can they be produced as desired?
4. (a) How does the Aston process for making wrought iron differ from the puddling process? (b) In what applications is wrought iron used instead of steel, even though steel is often less expensive?
5. What furnace produces the largest tonnage of steel? What furnace produces the cheapest steel?
6. (a) What gives a furnace the name "acid" or "basic"? (b) What impurities are removed in the basic open hearth furnace, and how does the acid open hearth compare in refining ability?
7. In general, how does a "rimmed" ingot differ from a "killed" ingot? What sort of products might be made from each?
8. What kind of cast iron would be used for (a) wear resistance, (b) impact resistance, (c) corrosion resistance, (d) good machinability, and (e) high hardness?
9. The percentage of carbon in a steel is one of its most important specifications. For instance, plain carbon steels with 0.10, 0.40, and 1.0 per cent are distinctly different types. How do they differ in hardenability, strength, ductility, machinability, and weldability? What is a typical use for each?
10. (a) Give at least two reasons for adding each of the following elements to steel: molybdenum, silicon, chromium, nickel, and tungsten. (b) In comparison with plain carbon steel, how much alloy steel is used? (c) Since alloy steels possess so many advantages, why are all steels not alloyed?

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## CHAPTER V

### NONFERROUS METALS AND ALLOYS

By D. BASCH, R. G. THOMPSON, and R. E. MOORE

**5.1. Introduction.** The nonferrous metals and alloys include all the metals, such as copper, aluminum, magnesium, and zinc, in which iron is not present in large quantities. The total annual production of all these nonferrous metals is only one-fifteenth that of iron and steel, but this figure does not accurately reflect their relative economic importance. A comparison of the total value of finished products would show that they have a much larger relative importance, since the nonferrous metals are used for parts such as electric wire, airplane structures, plumbing fittings, clockwork, and small machine parts whose finished value is high. Many nonferrous metals, for instance the precious metals gold, platinum, etc., are used only in small quantities by industry, and so are not discussed here. Many others are used only as alloying agents and are not important in their own right. This discussion will be limited to those nonferrous metals used in pure form or as base metals for alloys of industrial importance.

In general, the nonferrous metals are used for parts upon which a great deal of fabrication (forming) is done. They are used mainly where the advantages gained from proper use of their characteristic properties justify their higher cost. No single property or group of properties will be the basis for every choice, but the choice is often based on one or more of the following criteria:

- |   |                           |
|---|---------------------------|
| 1. Ease of fabrication.                 | 5. Strength.              |
| 2. Corrosion resistance.                | 6. Modulus of elasticity. |
| 3. Electrical and thermal conductivity. | 7. Color.                 |
| 4. Weight.                              |                           |

The first item, ease of fabrication, is a general term referring to casting, forging, rolling, welding, or machining properties of the material. Several of the nonferrous metals and alloys are particularly easy to cast because of high fluidity when molten, and low melting temperature. Their melting temperatures are usually well below those of steel molds, so such high production processes as permanent mold, die, and cold chamber pressure casting are possible with them. Many are malleable

and ductile while hot, thus permitting hot forming; many are also easily cold formed. Some of them are difficult to machine, but special machining grades of alloys are available. Their fabrication properties vary so widely that some metal or alloy can be obtained for nearly every process.

Most of the nonferrous metals resist corrosion by certain environments, but there is no metal which will resist all corrosive influences. There are nonferrous metals, or combinations of them, however, which will resist nearly any particular kind of corrosive attack. Some corrosion properties will be mentioned in this chapter, but more complete discussion on the corrosion of metals is given in Chapter VII.

The electrical and thermal conductivities of the nonferrous metals vary widely from very much above those of the ferrous metals to well below them. Copper is fairly inexpensive and has high conductivity, so it is used for electrical conductors. By comparison, some nickel alloys have very low conductivity, and so are used in electrical resistance wire. (See Chapter IX.)

The density of the nonferrous metals varies from one-fourth that of iron to much more than iron. The light-weight metals, magnesium and aluminum, are used in parts for high-speed, light-weight machines, and for transportation equipment.

On a volume basis, the strength of the nonferrous metals is without exception below that of the strong steels. Compared on a weight basis, however, the strong alloys of aluminum and magnesium are as strong as the steels. The heavier nonferrous metals and alloys are never used for their strength alone because steel is stronger and cheaper.

Several of the nonferrous metals, notably the light-weight ones, have low moduli of elasticity. This means that where a given rigidity or stiffness is required in a part, it would be made with a deeper cross-section if constructed of aluminum or magnesium than if of steel; but the larger light-weight metal part would probably weigh less.

In selecting the material for architectural fittings or household equipment, the color or finish is often important. Several of the nonferrous metals, particularly aluminum, nickel, and their alloys, are used for smooth finish and bright silvery color. Copper and its alloys form a whole set of red, gold, and yellow metals.

Besides the seven general bases which have been used for comparison of the nonferrous metals, there are other bases which may be of even greater importance in particular cases. These characteristics include cost, mechanical properties, influence of expected impurities on properties, forms available, and methods to be used in fabrication. They will be discussed briefly in the following sections.

### COPPER AND ITS ALLOYS

**5.2. Grades of Copper.** *Electrolytic Copper.* In the United States, copper is commonly extracted from low grade sulphide ores (1 to 2 per cent copper). After concentration, the ore is roasted and the sulphur content reduced to the proportion best for subsequent operations. Then the roasted ore is smelted in the reverberatory furnace to a mixture of copper and iron sulphides called *matte*. The molten matte is charged into a converter (similar to the Bessemer, Fig. 4.7), where streams of air oxidize and blow out the sulphur, first from the iron sulphide, permitting the iron present to go into slag. The product, *blister copper*, is further refined in a reverberatory furnace, and then cast into *anode bars* for electrolytic refining. During electrolysis, spongy copper forms on the cathode; afterward it is melted, treated to reduce oxides, and cast into molds. The most commonly used reducing method is the stirring of the melt with a green log, an operation called "poling." The product, as cast, will contain up to 0.07 per cent oxygen, and is known as *electrolytic tough-pitch copper*. Its properties would be much improved for some applications if its oxygen content were lower.

\* *Oxygen-Free and Deoxidized Copper.* The source of most of the oxygen in electrolytic tough-pitch copper is the hot oxidizing furnace atmosphere. If the melt is protected by a furnace atmosphere of chemically inert gas, and if the casting is done under similarly protected conditions, a high grade oxygen-free copper can be produced.

Low-oxygen-content copper may also be produced by deoxidation with a strong reducing agent such as phosphorus or silicon, but this copper has 10 to 15 per cent lower conductivity than electrolytic tough-pitch copper. A high conductivity grade of deoxidized copper can be made by carefully controlling the use of phosphorus, or by employing calcium, lithium, or boron, which leave no metallic residue in the copper.

*Lake Copper.* Deposits of native copper (crystals of nearly pure copper) are mined in northern Michigan. This *lake copper* is of such high purity that all refining is done in the blast furnace; after refinement the metal contains about 10 oz of silver per ton (0.03 per cent) and sometimes up to 0.3 per cent arsenic. If no arsenic is present, it has a conductivity equal to that of electrolytic copper. If arsenic is present in appreciable quantity, it is known to the trade as "arsenical lake copper," and its conductivity is not as good as that of the electrolytic grade. It does have better resistance to scaling and corrosion at high temperature, however, and has been used principally for condenser tubing and fire box parts.

Although the lake region was the principal United States source of copper before 1900, economical methods of working the low grade sul-

phide ores have greatly reduced its importance. When the demand for arsenical or silver-bearing copper is greater than the supply, the deficiency may be made up by adding arsenic or silver to electrolytic copper.

**5.3. Characteristics of Copper. Conductivity.** The high electrical conductivity of copper (second only to silver) has led to use of large quantities in electrical wire and machines. In such applications, the conductivity is important, but unfortunately, the usual alloying agents and impurities, except for silver, reduce it. The International Standard resistance for annealed copper is 0.15328 ohm per m g at 20 C (10.371 ohms per cir mil ft), and the conductivity of a copper sample is expressed as a percentage of the conductivity of this standard sample. Since the establishment of this standard, refining methods have been improved so much that copper of higher conductivity than the standard is now fairly common. Some samples run as high as 102 per cent conductivity, and a minimum standard of 99.3 per cent is frequently used. Electrolytic ingots usually have above 97.6 per cent conductivity.

**Recrystallization.** Copper is usually cold worked to its final size or shape, e.g., wire is drawn through dies, bar and sheet are rolled. This working, through the mechanism of work hardening, increases the strength and hardness but decreases the ductility.

If copper which has been cold worked is heated above the recrystallization temperature (400 to 500 F), it will return to its original soft, weak, and ductile condition (see Fig. 5.1). In general, the more it has been cold worked, the lower the temperature at which it will soften. Fig. 5.2 shows that copper which has been reduced 4 or 6 Brown and Sharpe gage numbers has a lower softening temperature than that which has been worked through only 2 Brown and Sharpe numbers.

To avoid a loss in strength by recrystallization of cold worked parts exposed to somewhat elevated temperatures, the recrystallization temperature must be raised. Several alloying agents may be used, but silver has the greatest effect. Fig. 5.2 shows that a few ounces of silver per ton raises the recrystallization temperature as much as 200 F. If cold worked copper wires or parts are to be soldered and must retain their cold work strength after soldering, they should be made of silver-bearing copper or of lake copper.

**Intercrystalline Failure.** If copper is moderately stressed at high temperatures and during a long enough period of time, it will fail. Table 5.1 shows results of tests on samples stressed at 16,000 lb per sq in., which was about half their ultimate strength at room temperature. The data show that the temperature necessary to produce a brittle intergranular fracture under stress and after a given time is at

least 100 F higher for silver-bearing copper than for electrolytic copper.

**Hydrogen Embrittlement.** The oxygen remaining in electrolytic tough-pitch copper is in the form of cuprous oxide ( $Cu_2O$ ). When this grade

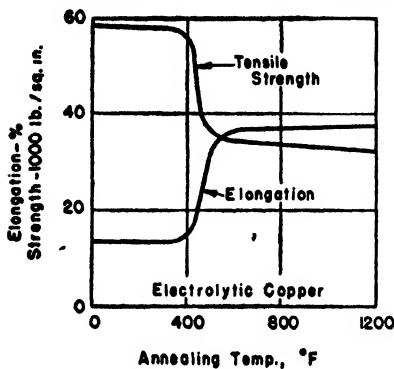


FIG. 5.1. Effects of annealing upon tensile strength and elongation of copper. (Bassett and Davis: *Data from Metals Handbook, 1939 Edition, American Society for Metals.*)

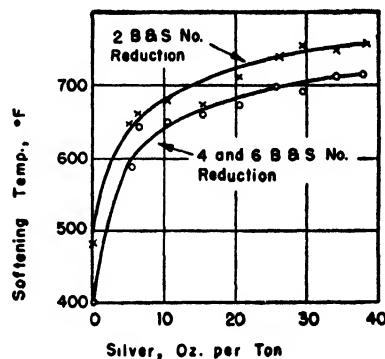


FIG. 5.2. Effects of silver and cold work upon the softening temperature of copper sheet. (Data from *Metals Handbook, 1939 Edition, American Society for Metals.*)

of copper is exposed to a reducing gas at temperatures above 750 F, the hydrogen in the gas diffuses into the copper and reacts with the cuprous oxide to form metallic copper and water vapor. The reaction is



Hydrogen diffuses into copper faster than the water vapor formed can escape by diffusion and an internal pressure sufficient to rupture the metal is built up. Cracks and holes appear at the grain boundary (see Fig. 5.3) and make the copper brittle.

TABLE 5.1. INTERCRYSTALLINE FAILURE OF COPPER

(Stress, 16,000 lb/sq in.)

Temp. F	Time to fail in hours	
	Electrolytic copper	14 oz/ton Silver-bearing Copper
482	1.5	46
455	2.0	157
392	19.	1048
337	110.	No failure

Wherever copper parts are to be exposed to reducing gases at temperatures above 750 F, they should be made of deoxidized copper.

**Fabrication.** Tests have shown conclusively that thoroughly deoxidized copper should always be specified for copper parts which are to be gas welded. This type of welding should not be used for tough-pitch copper because the copper would become spongy and porous at the weld. Spot or seam welding of high-conductivity copper is not done commercially unless the surfaces have been tin plated. Neither deoxidized nor electrolytic grades can be cut by an oxidizing gas flame because of their high thermal conductivities. They are, however, easily butt welded, silver brazed, and soldered.

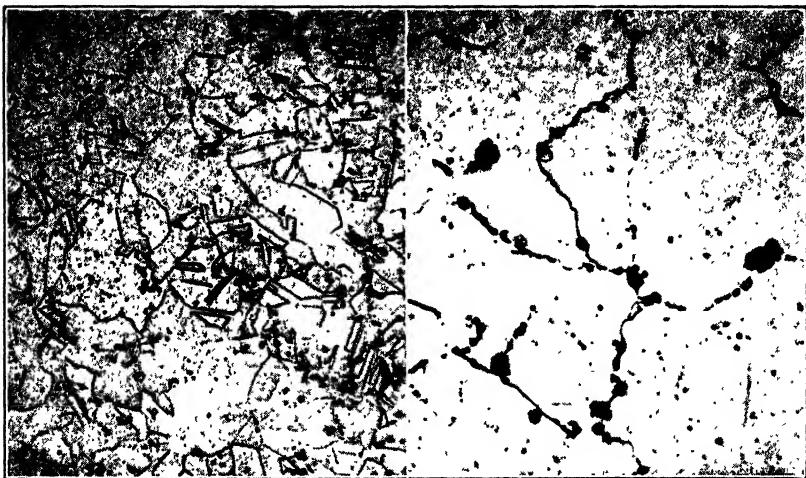


FIG. 5.3. Left, photomicrograph of annealed tough pitch copper X250. Right, photomicrograph of sample on left after two hours at 800 C in hydrogen X250. Note voids along the grain boundaries.

Copper castings are made almost entirely in sand molds. The technique of casting high-conductivity copper is especially difficult since considerable skill is required in handling the reducing agents. The molten metal is viscous and will not fill a mold of great intricacy. Copper is hot short and the hot casting will break as it cools if the mold or the design prevents shrinkage. If very high conductivity is not required, one of many casting alloys may be used. They are stronger and more easily machined and handled in the foundry, and as a result the finished casting will be cheaper than if made of high-conductivity copper.

**5.4. Copper-Zinc Alloys.** The most widely used copper alloys are brasses. Basically, they are binary alloys of copper with as much as 50 per cent zinc, but often their properties are modified by addition of

other elements in small amounts. The brasses are stronger than copper and are used in structural applications, but the increase in strength sacrifices both electrical and thermal conductivity.

Brasses containing more than 64 per cent copper are structurally a single-phase solid solution of zinc and copper, termed the "alpha" phase (see Fig. 5.4). They are easily cold worked, and their ductility increases with increase in zinc to a maximum at 36 per cent zinc, 64 per cent copper. With more than 36 per cent zinc, the brittle "beta"

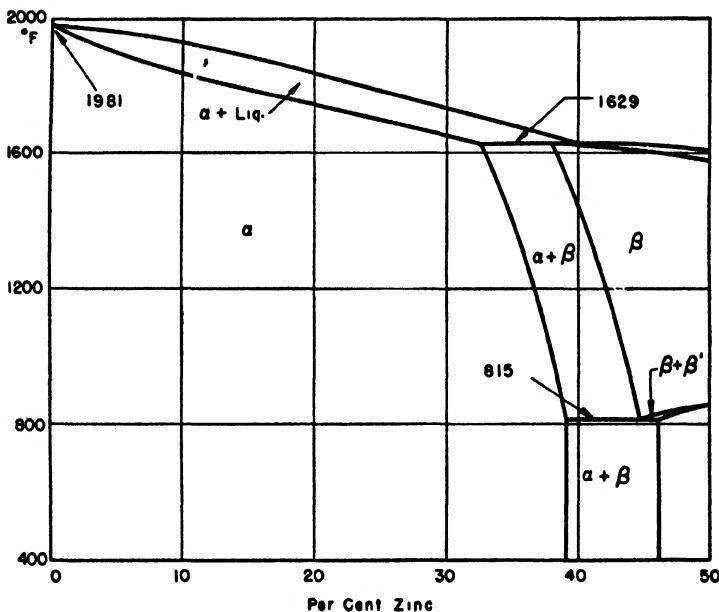


FIG. 5.4. Equilibrium diagram of copper-rich portion of copper-zinc alloy system.

phase appears along with the alpha, making the alloy increasingly difficult to cold work. The high zinc brasses are therefore most easily *hot* worked, while the lower zinc brasses (alpha brasses) are formed more easily while *cold*.

All of the brasses containing up to 40 per cent zinc are useful, and there are dozens of varying compositions. Slight modifications of composition usually do not produce important changes in properties. Therefore, for the purpose of the following discussion, the common alloys will be divided into groups. The names of the alloys in each group are, in general, unrelated, but they are used by custom throughout the trade and will be given when expedient.

*Brass Containing 5 to 15 Per Cent Zinc.* Brasses containing up to 15 per cent zinc have good corrosion resistance. Like copper, they are ductile and suitable for extreme cold working, but are difficult to machine. *Gilding brass* (5 Zn) and *commercial bronze* (10 Zn) are used for bullet jackets and articles exposed to the weather. Color is often the basis of selection between them. Gilding brass is nearly copper colored; commercial bronze has a true "bronze" color. *Red brass* (15 Zn), also called *rich low brass*, is used for imitation gold jewelry. It has the best corrosion resistance of all the brasses and is superior to copper for handling hard water, and is consequently used for plumbing hardware, pipe, radiator cases and condenser tubing.

*Brasses Containing 20 to 36 Per Cent Zinc.* Brasses containing between 20 and 36 per cent zinc are very readily cold worked. Their advantages over brasses containing less zinc lie in low cost, since zinc is cheaper than copper, and in superior machinability. Brasses containing 20 to 36 per cent zinc can also be hot worked, but only if their constituents are very pure. This is a new development, since high purity zinc must be used and it has not been available commercially until the last few years.

The medium zinc brasses are subject to corrosion which works in either of two ways. When exposed to acids or salt solutions (such as hard water), zinc may be removed electrolytically. This *dezincification* leaves spongy layers of copper, often called *plugs*, on the surface.

Under the influence of corrosive media and stress, brasses with more than 15 per cent zinc fail by *season cracking*, sometimes called *corrosion cracking*. The failure occurs in areas where stress is maximum; and to minimize the danger of failure, stresses remaining after cold working should be relieved by annealing. In service, however, load stresses can scarcely be avoided. According to recent tests, the load stress which eventually produces season cracking is very much less than the yield stress.

*Low brass* (20 Zn) has fair corrosion resistance, being subject to dezincification and season cracking under only the most severe conditions. Both low brass and *brazing brass* (25 Zn) are deep drawn, spun, and cold formed with ease. They are used for musical instruments, drawn eyelets, and for ornamental architectural work. Brass containing 30 per cent zinc is very tough and ductile, since it is high in zinc. It is particularly suited to deep drawing or spinning and is usually called *cartridge brass*. Until recently, cartridge cases have been manufactured entirely by cold working. Today, however, a high purity grade of zinc is used, as mentioned above, and hot working in the initial forming of the part is employed, thus avoiding repeated cold rolling and annealing cycles.

*Admiralty metal* is made by the substitution of 1 per cent tin in cartridge brass. The usual composition is 70 copper, 29 zinc, 1 tin, with as much as 0.05 per cent arsenic, which tends to inhibit dezincification. The tin gives the alloy fair resistance to corrosion by sea water. This has led to its use in marine condenser tubing.

*Aluminum brass* (76 Cu, 22 Zn, 2 Al) forms a tenacious surface film and has been used in recent years for condenser tubing where the alloy must withstand erosion by high velocity water.

*Common high brass* (34 Zn), also called *yellow brass*, is the cheapest of all the brasses which may be cold worked. Large quantities of screws, rivets, and tubing are made of high brass, although it is subject to corrosion. Parts which are cold formed should be annealed after the final forming to inhibit season cracking.

*Brasses Containing 40 Per Cent or More Zinc.* Brasses containing more than 35 per cent zinc contain the brittle beta phase and are difficult to cold work. They may, however, be hot worked. *Muntz metal* (40 Zn) is worked at a red heat and is not malleable when it is cold. It is used only in mildly corrosive media, and then principally because of its low cost.

*Naval brass* has approximately the same composition as Muntz metal, except for the addition of a small amount of tin (40 Zn, 0.75 Sn, balance Cu). As with Admiralty metal, the tin is added to give resistance to corrosion by sea water.

Extrusion is used not only for tubing, but for many irregular shapes. Brasses which are easily hot worked are often extruded when hot, while others are extruded cold. The hot extruding alloys are most often used, however, because the power used in extrusion is a minimum. An alloy which has excellent plasticity at high temperature contains 37 per cent zinc and 4 per cent lead.

Up to 3 per cent lead is often added to brass to improve machining properties because it causes the chips to break free. Where it is necessary to do severe cold forming and machining on the same part, 1 per cent lead may be used, since a 3 per cent lead brass would be easily broken in cold forming. An alloy which is easily hot worked and machined is forging rod (38 Zn, 2 Pb, 60 Cu). Lead does not affect the corrosion resistance or conductivity of brass.

Brasses containing over 40 per cent zinc are not widely used. One application is as a brazing spelter of half-and-half composition (50 Zn, 50 Cu).

Practically no straight brasses, that is, plain copper and zinc alloys, are used for castings. Some of the complex brasses, primarily those with the addition of manganese and other elements, are used in quantity

for castings. Scrap brass is often cast, however, if accurate control of the properties is unnecessary.

**5.5. Other Copper Base Alloys.** Alloys of copper with other materials than zinc are usually called bronze, although the application of the term is loose, as indicated by the brass called "commercial bronze." Like the copper-zinc alloys, the bronzes may be hardened by cold working. In addition, some of the bronze alloys can be hardened by precipitation heat treatment.

*Alloys Not Hardenable by Heat Treatment.* **SILICON BRONZE.** *Silicon bronze* has an average composition of 96 per cent copper, 3 per cent silicon, and 1 per cent manganese or zinc. It has the good general corrosion resistance of copper, combined with higher strength, and in addition can be cast, rolled, spun, stamped, forged, and pressed either hot or cold and can be welded by all the usual methods. Common uses are parts for boilers, tanks, stoves, or wherever high strength and good corrosion resistance are required. It is exceptionally easy to weld by any common method, but the silicon content tends to make it difficult to solder and braze. Duronze, Olympic, Everdur, and Herculoy are trade names.

**PHOSPHOR BRONZE.** Copper-tin alloys deoxidized with phosphorus are called either *tin bronze* or *phosphor bronze*. The range of tin is from less than 1 per cent to 11 per cent, and the phosphorus ranges from an almost negligible amount up to 0.5 per cent. Strength and hardness increase with tin content, but so does the cost. The tin bronzes have high strength, resilience, and resistance to wear and fatigue, properties which recommend them particularly for use as a spring material. To improve machinability, up to 4 per cent lead may be added. Shafts and bushings with moderately good wear resistance are made of the free machining (leaded) phosphor bronze.

**CUPRO-NICKELS.** Copper and nickel form a complete series of solid solutions, and show no sudden change in properties with change in composition. Alloys with 20 to 30 per cent nickel are used under severely corrosive conditions. Large quantities are used for tubing in oil field applications and for marine condensers. Although nickel is an expensive alloying agent, its use is often justified because of the superior resistance of its alloys to corrosion.

An alloy of 45 per cent nickel, called Constantan, has high electrical resistance and low temperature coefficient of resistance, qualities which make it an ideal material for electrical resistance wire. Its high thermoelectric force when in contact with other common metals makes it a good thermocouple material.

Nickel silver contains zinc in addition to copper and nickel. Although

there are many variations in composition, an alloy containing 64 copper, 18 nickel, 18 zinc is by far the most widely used. It has a silver color, good corrosion resistance, and fairly high electrical resistivity. Nickel silver is used as a base for plated jewelry and tableware, for ornamental metal work, food handling equipment, marine fittings, and for electrical resistance wire and springs.

*Hardening Alloys.* Some of the alloys of copper can be hardened by phase transformation and decreased solubility, as steel is hardened. Others may be solution heat treated and precipitation hardened.

**ALUMINUM BRONZE.** Aluminum bronze is hardened through phase change and decrease in solubility. It is a versatile alloy, since its properties may be controlled over a wide range not only by variation of alloying agents, but also by heat treatment. With up to 7.5 per cent aluminum, the copper-aluminum alloys are extremely ductile. When metal must be severely cold worked, aluminum bronze is often substituted for brass because of its superior strength and resistance to corrosion.

An alloy of 7.5 to 9.5 per cent aluminum and up to 1.5 per cent iron with copper is used as cast, without hardening, for good corrosion and shock resistance. Increase of aluminum to 12 per cent and iron to 4 per cent gives an alloy which, as cast, has a very high endurance limit and resistance to shock. It is used for heavily loaded gears in machine tools, steel mill drives, and construction machinery. Cams, rollers, and slides utilize its excellent resistance to wear. Aluminum bronze high in aluminum (9.5 to 12 per cent) and iron (1.5 to 4 per cent) may be hardened to a degree comparable with the alloy steels, yet may have superior resistance to abrasion. Though brittle, it is valuable in such parts as dies and sliding machine members.

**BERYLLIUM BRONZE.** Beryllium bronze (beryllium copper) is a precipitation hardening alloy usually composed of about 2 per cent beryllium and the remainder copper. It is usually solution heat treated and cold worked to some extent by the supplier before fabrication by forming and machining. After machining, it may be hardened by aging in a furnace for several hours at 500 to 600 F. When hard, it has better wear resistance than phosphor bronze. Heavily loaded bushings, seats, or springs subject to vibration or shock are usually made of beryllium bronze, even though it is very expensive. The springs have a remarkable freedom from hysteresis and elastic drift and retain their springiness to a greater degree than springs of any other corrosion resistant material.

**CHROMIUM BRONZE.** Chromium bronze is a precipitation hardening alloy of copper with up to 1 per cent chromium. It has not as yet been used in large quantities.

**ALUMINUM AND ITS ALLOYS**

**5.6. Commercial Aluminum.** Although aluminum is a relatively new metal in industry, it has rapidly come into wide use, particularly because of its adaptability to the expanding airplane industry. Increasing production has brought about progressive reduction in cost until now its price per pound is almost as low as that of copper.

The principal ore of aluminum is bauxite,  $\text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ . After the ore is mined, it is crushed, concentrated by chemical means, and roasted to drive off the water. This leaves alumina,  $\text{Al}_2\text{O}_3$ , which is reduced (deoxidized) by electrolysis of a molten solution. Because the electrolyte is an impure mineral, the aluminum produced usually contains considerable quantities of other metals. The nominal purity of structural aluminum is 99.2 per cent, while that of aluminum conductor is 99.5 per cent.

*Effect of Impurities.* The principal impurities in commercial aluminum are iron, silicon, and copper (zinc is also present in scrap aluminum); their quantities can be approximately controlled by the producers. They do not always have an undesirable effect on the properties, and in many applications their effect is good. For instance, chemically pure aluminum is very soft and weak; commercial aluminum has about twice the strength of the pure grade. The thermal and electrical conductivities of commercial aluminum are, on the other hand, only slightly below the conductivities of chemically pure aluminum.

**5.7. Characteristics.** Aluminum and its alloys are used principally in applications which demand one or more of its outstanding characteristics: (a) good strength, (b) light weight, (c) high thermal and electrical conductivity, and (d) good corrosion resistance.

*Weight and Strength.* Aluminum and aluminum base alloys have densities of about 0.10 lb per cu in., compared with 0.32 for copper, 0.28 for steel, and 0.065 for magnesium. By volume, aluminum is less than half as expensive as copper; it is the cheapest material for nonmagnetic parts of a given volume.

Commercial aluminum in the annealed or cast condition has a tensile strength about one-fifth that of structural steel. The strength may be more than doubled by cold working; and by alloying aluminum with various other metals the strength may be even further increased. The ratios of strength to weight for some of the hardened aluminum alloys are as high as for any other structural material. Although some steels have comparable strength-to-weight ratios, the structural aluminum alloys have proved themselves superior in many applications, particularly in light-weight transportation equipment. Their superiority can be explained as follows.

Structural members are often column loaded and fail by buckling. The load sufficient to cause failure of the entire column depends upon the moment of inertia of the column cross-section. In order to increase the load capacity for a given amount of material, special shapes, such as I-beams or tubes, are used. The effective increase is limited; if any part of the column is made too thin, it will fail by local buckling. A material like aluminum alloy, which has thick sections in proportion to its weight, is ideal for light-weight columns. A typical application is in a stressed airplane skin, where compressive stresses between points on the skin may cause it to wrinkle. It is easy to see that an aluminum alloy skin  $\frac{1}{16}$  in. thick would stand a great deal more column loading than a steel sheet 0.02 in. thick, even though they are of the same weight and their strengths in direct tension or compression would be about equal. This comparison holds true for the structural members within the airplane; and for small, light planes, wood may even be preferred to aluminum.

*Conductivity.* The thermal and electrical conductivities of commercially pure aluminum are about 60 per cent of those of copper. This is high enough to bring about its use as the conductor for many electric power lines. In order to have the same resistance as a copper conductor, the aluminum wire should have a 65 per cent larger cross-sectional area. Its weight would still be only half that of an equivalent copper wire, and if the cost of aluminum and copper per pound were the same, the aluminum conductor would cost only half as much as the copper one. However, this economy cannot be fully realized because the aluminum is weak and must be reinforced by a steel core in order to support its own weight and service loading.

Bare aluminum conductor has, during normal years, consumed about one-sixth of the United States aluminum production. Insulated aluminum cable has not been used because the large wire cross-section makes it necessary to use about 30 per cent more insulating material than for a copper wire having the same resistance, thus raising the over-all cost of insulated aluminum conductor above that of insulated copper.

*Fabrication.* The melting point of pure aluminum is 1215 F; alloys usually melt at lower temperatures. These low melting points make them unsuitable for high temperature applications, but do facilitate casting in sand, permanent molds, or under pressure in dies. The physical properties of aluminum alloys cast in metal molds are, in general, better than those of the same alloys cast in sand. The metal mold chills the molten metal far more rapidly, and the grains are given only a short time to grow. In a casting which has a varying cross-

section, the thinnest sections will cool first and have the finest grains. Test coupons cast as an integral part of the casting, or separately cast to a standard diameter, do not, therefore, represent the strength of all the parts. The thicker sections will be weaker, the thinner ones will be stronger.

Pure aluminum is seldom used for castings because of its hot shortness and high shrinkage. It is used only where high conductivity is demanded, for example in cast squirrel-cage rotor windings.

Aluminum and aluminum alloys are relatively brittle in ingot form, so the first forming is usually done at a plastic temperature of 750 to 900 F. The hot forming may be continued at 500 to 900 F, depending upon the type of alloy and the process. Many forms, such as tubing, rod, or plate are extruded or hot rolled to their final forms, although some tubing and other forms such as wire and sheet are finished by cold working.

A relatively new development in aluminum products is the use of pressings, which are made from suitably shaped slugs of alloys and squeezed into shape in a press. Pressings may be made hot or cold, using any alloy that can be extruded or forged.

Aluminum is inherently very reactive and it spontaneously forms a thin oxide film when exposed to the air. This oxide film must be removed and prevented from reforming while soldering; otherwise a very weak joint will result. Even with proper precautions, the soldering of aluminum is usually unsatisfactory, because the joint between aluminum and any solder thus far developed will, in time, decompose electrolytically.

The oxygen coating offers some difficulty to welding. In nonpressure welding, the oxide must be removed by fluxes, and for resistance welding it may be necessary to brush off the oxide coat or remove it by etching. If these precautions are taken, however, good welds can be made by any of the usual welding methods.

Aluminum has a coefficient of thermal expansion 50 per cent greater than copper and twice that of steel and cast iron. Where large temperature changes are encountered in an assembly of aluminum parts with those of other metals, allowance must be made for this difference in expansion.

The machining of aluminum is not difficult, but it varies widely for some alloys. Although special tools and techniques have been developed, the tools used for other harder metals can be used with satisfactory results if production quantities are small.

*Corrosion Resistance.* The thin oxide coating which forms on aluminum and its alloys serves as protection against corrosion. Erosion or

abrasion will, of course, remove this oxide and will accelerate corrosion. Constant rubbing of parts may make this particularly severe.

Commercially pure aluminum (2S)<sup>1</sup> is often used for such shapes as sheet, tubing, and rod where good general corrosion resistance is required. An alloy with approximately equal corrosion resistance and considerably higher strength contains 1 to 1½ per cent manganese, the remainder aluminum (3S). Alloys of aluminum with silicon and magnesium also have good resistance to corrosion, but zinc and iron alloys appear to have less corrosion resistance.

The alloys of aluminum with copper, tin, or zinc are attacked to various degrees by local electrolytic corrosion. The local cells may be broken up, however, by periodic cleaning of dirt and moisture from the surface. Oil or wax is good for temporary protection.

*Oxide Coatings.* A heavy surface oxide may be artificially produced by either of two methods. One method, which produces a film with considerably greater protective power than the natural oxide coating involves boiling the metal in a chromate or carbonate solution.<sup>2</sup> A second method, called *anodizing*, is more expensive, but causes formation of an even better protective coating. In this method, the article is made the anode in an electrolyte such as sulphuric acid, chromic acid, or oxalic acid. The color of the anodic coating may be controlled by surface condition and composition of the alloy, by the type of electrolyte, or by dyeing the anodic coat. Both the chemically and anodically produced oxide films are improved by "sealing" with dichromate solutions. In severely corrosive atmospheres, anodic coatings must be kept clean in order to prevent breakdown of the coating and pitting of the aluminum alloy beneath.

*Painting.* Before painting, a suitable primer or treatment must be used to make the surface chemically inert. An anodic coating is an ideal paint base, although in many cases an anodic coating is painted only for appearance, not to improve its corrosion resistance. The surface can be prepared more cheaply by one of several chemical immersion treatments, but they do not give corrosion protection equal to anodizing. For best corrosion resistance, the surface of the paint should be impermeable to moisture, and for this purpose aluminum paint with a synthetic resin is excellent.

*Metallic Coatings.* Nearly all of the alloys have poorer corrosion resistance than commercial aluminum, and when corrosion protection is needed, some alloys are coated with commercially pure aluminum. The coating oxidizes and gives high electrolytic corrosion resistance,

<sup>1</sup> Designation used by the aluminum companies in the United States.

<sup>2</sup> Trade names are Alrok and Pylumin.

but in addition its electrolytic properties<sup>1</sup> are such that it prevents the corrosion of the base metal at the sheared edges or where the coating is deeply scratched. The entire coating will be corroded away before the base metal in the vicinity will be disturbed. The usual thickness of the coat is about 5 per cent of the total thickness of the part, and it is applied during the hot rolling of the shape. Common trade names are Alclad and Pureclad.

Rolled shapes, castings, and assemblies which cannot be readily clad may be protected by a sprayed coating of aluminum, zinc, or cadmium. These deposits are porous, and their protective action is caused only by their electrolytic properties.

Aluminum can be plated with zinc, cadmium, nickel, and chromium, all of which offer mechanical protection. Zinc and cadmium also provide electrolytic protection against corrosion, but nickel and chromium platings provide their respective corrosion resistances only if their coating is continuous.

**5.8. Alloys.** The aluminum alloys are stronger than pure aluminum. Some of them can be hardened by precipitation heat treatment, and all can be hardened by cold working.

*Nonprecipitation Hardening Alloys.* The aluminum casting alloys generally contain higher percentages of alloying elements than the alloys used in wrought forms. The higher percentages of added elements facilitate casting but make working more difficult.

Copper is the principal hardening ingredient used in aluminum. Several copper alloys are used, but for general sand and permanent mold casting, an 8 per cent copper alloy has been most popular. For best casting and physical characteristics, iron and silicon should be accurately controlled at about 1 per cent each. The cost of the finished product is often lower when made of the 8 per cent copper alloy than if made of other alloys, and this has been one reason for its wide use for cast automobile engine crankcases, oil pans, and transmission cases. Its principal disadvantage is relatively poor corrosion resistance.

A 5 per cent silicon alloy has been used considerably for sand and permanent mold castings because it has good resistance to corrosion and excellent casting qualities (high fluidity and freedom from hot shortness). It is generally suitable for pressure-tight castings and can be made in thin sections.

The 13 per cent silicon alloy is used principally for die casting. It has the good casting properties and corrosion resistance characteristic of silicon alloys.

Of the wrought aluminum alloys which cannot be precipitation

<sup>1</sup> The mechanism of electrolytic protection is discussed in Chapter VII.

hardened, the 1.25 per cent manganese alloy is one of the more important. It is stronger and harder than pure aluminum, and, unlike other alloys, its corrosion resistance is about as good as that of pure aluminum. It is used for conduit and pipe, and for cooking utensils, since it retains its work hardness very well after exposure to elevated temperatures.

An alloy which has considerably higher tensile and yield strengths than the aluminum-manganese alloy contains 2.5 per cent magnesium and 0.25 per cent chromium, besides aluminum. It has good corrosion resistance, especially to salt water, good workability, and high fatigue resistance.

*Precipitation Hardening Alloys.* Some of the aluminum alloys, when water quenched from high temperatures and then aged either naturally at room temperature or artificially at a slightly elevated temperature, show remarkable increases in strength and hardness. They are called the *strong alloys* of aluminum.

The best known of the precipitation hardening aluminum casting alloys contain 4 per cent copper and small but accurately controlled percentages of iron and silicon. These alloys have fairly good resistance to damage by corrosion, although their surface may be blackened. They are somewhat harder to cast than the 8 per cent copper alloys, but the difficulty has not prevented their wide use. The castings may be solution heat treated and quenched, after which they are in the condition of maximum ductility and impact resistance. If high yield strength rather than impact resistance is desired, the casting is hardened by furnace heating, which causes precipitation.

There are two groups of precipitation hardening aluminum-silicon alloys, both of which have better casting characteristics and corrosion resistance than the aluminum-copper alloy. The 5 per cent silicon, 1.25 per cent copper, 0.5 per cent magnesium alloy was developed for liquid cooled cylinder heads, and consequently is used wherever strong, pressure-tight castings are needed. A 7 per cent silicon, 0.3 per cent magnesium alloy is also used for complicated and pressure-tight castings, and, like the 5 per cent silicon alloy, it is particularly adapted to permanent mold casting.

Alloys of aluminum with about 10 per cent magnesium may be precipitation hardened to obtain a tensile strength as high as that of any common aluminum base casting alloy. They also have good impact strength and corrosion resistance, but because of the high magnesium content, special foundry techniques must be used to avoid surface oxidation of the casting.

A common precipitation hardening wrought alloy is Duralumin, or 17S (4 Cu, 0.5 Mg, 0.5 Mn), which hardens spontaneously in about

4 days at room temperature. The hardening begins so rapidly that forming should be done during the first few hours after quenching. If the forming is delayed, the aging of the alloy should be suspended by keeping the parts in liquid air or some other drastic freezing medium.

The inconvenience of handling the alloys which age spontaneously has led to development of new alloys whose compositions are variations upon that of Duralumin. They will not age harden at room temperature, but are hardened by furnace heating to 300 or 350 F for 8 to 24 hr.

An alloy known to the trade as 53S (0.7 Si, 1.25 Mg, 0.25 Cr) is adapted to severe drawing and forming when in its soft state. When forming is complete, the part can be precipitation hardened by aging in a furnace without causing distortion. Unlike most of the other strong alloys of aluminum, 53S has excellent resistance to weathering and corrosion. Variations in its composition produce alloys which have better mechanical properties for certain applications, but which have less corrosion resistance.

### MAGNESIUM

**5.9. Characteristics.** Magnesium is the lightest of the commercial metals; its density is about two-thirds that of aluminum, one-fourth that of steel. The pure magnesium is seldom used as a structural material because of its low strength, but its alloys are stronger, and many of them can be hardened by precipitation heat treatment. The uses for magnesium in alloys for portable or high-speed machinery have multiplied many fold during recent years and its price has dropped correspondingly. Although the price is still above that of aluminum, increased production may soon enable magnesium to compete with aluminum in many applications.

The strength-to-weight ratio of the precipitation-hardened magnesium alloys is comparable with that of the strong alloys of aluminum or with the alloy steels. Magnesium alloys, however, have a lower density and stand greater column loading per unit weight. They are also used when great strength is not necessary, but where a thick, light form is desired. Examples are complicated castings, such as housings or cases for aircraft, and parts for rapidly rotating or reciprocating machines. The strength of magnesium alloys is reduced at somewhat elevated temperatures; temperatures as low as 200 F produce considerable reduction in the yield strength.

Magnesium and its alloys have very good resistance to corrosion by most atmospheres. In industrial or humid areas, however, corrosion is most rapid and will, over a period of years, cause powdering of the surface. The rate of corrosion is very slow compared with the rusting

of mild steel in the same atmosphere. Immersion in salt water is very dangerous, but a great improvement in resistance to salt water corrosion has been achieved, especially for wrought materials, by reducing some impurities, particularly nickel and copper, to very low proportions.

Even with protective treatment, corrosion troubles may be expected sooner or later in poorly designed assemblies where moist air is trapped or where rain is allowed to collect. Where such designs are avoided, unpainted magnesium alloy parts that are oily or greasy will operate indefinitely with no sign of corrosion. Magnesium alloy parts are usually painted, however, except where the conditions of exposure are mild. To assure proper adherence of the paint, the part is cleaned by grinding, buffing, or blasting, then given an acid dichromate dip.

**5.10. Fabrication. Hot and Cold Working.** Magnesium alloys harden rapidly with any type of cold work, and therefore cannot be extensively cold formed without annealing. Sharp bending, spinning, or drawing must be done at about 500 to 600 F, although gentle bending around large radii can be done cold. Slow forming gives better results than rapid shaping. Press forging is preferred to hammer forging because the press allows greater time for metal flow. The plastic forging range is 500 to 800 F, and if the metal is worked outside this range, it will be easily broken.

**Casting.** The magnesium alloys, especially those which may be precipitation hardened, are used in casting. Sand, permanent mold, and die casting methods may be used, but plaster of Paris casting has not yet been perfected.

Sand casting in green sand molds requires a special technique because the magnesium will react with moisture in the sand, forming magnesium oxide and liberating hydrogen. The oxide forms blackened areas called *burns* on the surface of the casting, and the liberated hydrogen may cause porosity. To prevent the reaction, inhibitors such as sulphur, boric acid, ethyl glycol, or ammonium fluoride are mixed with the damp sand. All gravity-fed molds require an extra high column of molten metal so the pressure will be great enough to force gas bubbles out of the casting and cause the metal to take the detail of the mold cavity. The thickness of the casting wall should be at least  $\frac{5}{32}$  in. under most conditions. Extra large fillets must be provided at all re-entrant corners, since stress concentrations in magnesium castings are particularly dangerous.

Permanent mold castings are made from the same alloys and have about the same physical properties as sand castings. Since the solidification shrinkage of magnesium is about the same as that of aluminum, aluminum molds can often be adapted to make magnesium alloy castings (although it may be necessary to change the gating).

Pressure cold-chamber castings are used for quantity production of

small parts. The rapid solidification caused by contact of the fluid metal with the cold die produces a casting of dense structure with excellent physical properties. The finish and dimensional accuracy are very good, and machining is necessary only where extreme accuracy is required. Usually these castings are not heat treated.

*Welding, Soldering, and Riveting.* Many of the standard magnesium alloys are easily welded by gas or resistance welding equipment, but they cannot be cut with the oxygen torch. Usually magnesium alloys are not welded to other metals because brittle intermetallic compounds may form, or because the combination of metals may promote corrosion. Where two or more parts are welded together, their compositions should be the same.

Soldering of magnesium alloys is feasible only for plugging surface defects in parts. The solders are even more corrosive than with aluminum, and should never be required to withstand any stress.

Riveted joints in magnesium alloy structures usually employ aluminum or aluminum-magnesium alloy rivets. Magnesium rivets are not often used because they must be driven when hot. Where aluminum alloy rivets are used under corrosive conditions, the rivet should be dipped in a bitumastic paint to insulate it from the magnesium. The rivet holes should be drilled, especially in heavy sheet and extruded sections, since punching tends to give a flaky structure at the edge of the hole and to cause stress concentrations.

*Machining.* Magnesium and its alloys have the best machining characteristics of the common metals. The power required in cutting them is small, and extremely high speeds (5000 ft per min in some cases) may be used. The best cutting tools have special shapes, but the tools for machining other metals can be used, although somewhat lower efficiency results.

When magnesium is cut at high speed, the tools should be sharp and should be cutting at all times. Dull, dragging tools operating at high speed may generate enough heat to ignite fine chips. Chips and dust from grinding can therefore be a fire hazard, so grinding should be done with a coolant, or with a device to concentrate the dust under water, and the magnesium grinder should not be used for ferrous metals since a spark might ignite the accumulated dust. If a magnesium fire should start, it can be smothered with cast iron turnings or dry sand, or with better materials prepared especially for the purpose. Water or liquid fire extinguishers should never be used because they tend to scatter the fire. Actually it is much more difficult to ignite magnesium chips and dust than is usually supposed, and for that reason they do not present great machining difficulties.

The special techniques which must at present be used in fabricating

magnesium (working, casting, joining) add considerably to the manufacturing cost. In selecting between aluminum and magnesium for a given part, the base cost of the metal may not give much advantage to either, but in most cases the manufacturing operations will make magnesium the more expensive.

**5.11. Alloys.** Practically all of the commercial magnesium alloys manufactured in the United States contain aluminum (3 to 13 per cent) and manganese (0.1 to 0.4 per cent). Many of them also contain zinc. A popular example is the casting alloy containing 6 per cent aluminum and 3 per cent zinc. It may be precipitation hardened to secure high strength and hardness. If copper and nickel impurities are kept to a minimum, the alloy has very good resistance to corrosion.

A magnesium alloy containing 9 per cent aluminum and 2 per cent zinc is used particularly for pressure resistance because it is claimed to be relatively free of microshrinkage.

#### ZINC

**5.12. Characteristics and Refining.** Zinc is a fairly heavy, bluish-white metal used principally because of its low cost, corrosion resistance, and alloy properties. Its density is slightly less than that of copper, but it costs only about half as much. The strength of zinc is not great, and static loads well below the ultimate strength will cause creep even at room temperature.

The temperature range through which zinc and its alloys retain their strength is relatively narrow. The upper limit is the recrystallization temperature, 100 to 115 C, above which they have very little strength. The lower limit for many parts is a freezing temperature, below which zinc alloys are brittle. If a part must stand shock at low temperatures, it should not be made of zinc.

The principal zinc ore is the sulphide, zinc blende. The ore is concentrated by flotation, after which it is roasted in the presence of air to yield zinc oxide. The oxide may be reduced either in a furnace or electrolytically. In the furnace reduction, a mixture of zinc oxide and coal is fired, the zinc is vaporized, reduced at high temperature, and then caught and liquefied in a condenser. The purity of the zinc produced varies with the type of ore but is usually not less than 98 per cent. When needed, zinc of 99.99+ per cent (special high grade) purity may be produced in large quantities by fractional distillation of the less pure zinc.

The electrolytic reduction of zinc is begun by dissolving the oxide in sulphuric acid. The resulting zinc sulphate solution is used as the electrolyte. The purity of the zinc produced depends upon the purity

of the electrolyte; if the electrolyte has been chemically purified, zinc of 99.99+ per cent can be produced by this method also.

In the less pure grades of zinc, the most common impurities are lead, tin, and cadmium. Their general effect is to harden the zinc and reduce its ductility and corrosion resistance. The quantity and kind of impurities present determine the exact properties and cost. There are characteristic uses for each of the several grades of zinc, which range from 98 to 99.99 per cent purity.

**5.13. Uses.** Table 5.2 shows the relative quantity of zinc used for various industrial applications.

TABLE 5.2<sup>1</sup>

<i>Application</i>	<i>Per Cent</i>
Galvanizing	43
Brass making	28
Die casting	18
Rolled zinc	9
Miscellaneous	2

<sup>1</sup> Data from Metals Yearbook, 1941, U. S. Department of Interior, Bureau of Mines.

**Zinc Coatings.** The protection of iron and steel from corrosion is done more often with zinc than with any other metal coating. The oldest and most important methods of applying the zinc coating are known as galvanizing. This is done either by dipping the iron in molten zinc or by electroplating. Hot dip galvanizing is done largely with the less pure grades of zinc, although high grade zinc is often used for wire coatings which must stand bending without flaking. In electrogalvanizing, the zinc may be obtained either from zinc anodes or by direct solution from the ore and subsequent purification in the electrolyte. The life of the galvanized material is proportional to the thickness of the coating. In order to achieve good adhesion, however, the surface of the iron must be carefully acid-dipped and scrubbed before galvanizing.

When the part to be coated cannot conveniently be galvanized, a zinc coating may be sprayed on the surface. Small parts may also be coated with a very uniform zinc surface layer by a process called Sherardizing.

**Brass Making.** All of the grades of zinc may be used in brass making, but the purity is of considerable importance in determining the physical properties. Brasses made with 10 to 36 per cent zinc were formerly hot short and very difficult to hot work. Today, however, special high

purity zinc makes it feasible to hot work these brasses, but zinc of lower purity is still used in most brass making.

**Die Castings.** Zinc alloys have been widely used in die casting because their over-all cost is low. The casting temperatures are moderate, and plastic inserts or insulated wire can be cast into the part. The pressures available in zinc die casting machines are high, and the castings can be made with good density, relatively little porosity, good dimensional accuracy, and in very thin sections.

Alloys containing zinc of low purity cannot be used in die castings since they decompose by intergranular corrosion, especially in warm, humid atmospheres. This is because aluminum, which is used in all die casting alloys, combines with any lead, tin, or cadmium which may be present and forms unstable phases. All the alloys recommended for die casting are therefore made from special high purity zinc. The alloy, as cast, is limited to minute percentages of the impurities lead, cadmium, and tin. Standard zinc base alloys contain approximately 4 per cent aluminum, as much as 2.5 per cent copper, and 0.1 per cent magnesium, besides zinc and minute impurities. They are known to the trade as *Zamak* alloys.

After casting there is a shrinkage of the order of 0.001 in. per in., which takes place over a period of weeks but which can be immediately brought on by annealing. After this is done, the dimensions of the die cast part are very stable, unless the casting alloy is high in copper. Parts containing 2.5 per cent copper may be expected to expand 0.001 in. per in. during a period of 5 yr, but those with lower copper content have better dimensional stability.

**Wrought Forms.** The wrought zinc of industry varies considerably in purity, and usually contains up to 1 per cent added copper. It is ductile and easily formed at room temperatures. Many such articles as dry battery cans, eyelets, and vanity cases are drawn from rolled zinc sheet or strip. Although cold working hardens the metal, the effect of cold work is lost at only moderately elevated temperatures. During the time zinc retains the effects of cold work it may have as much as double the strength along the length of the distorted grains as across them.

**5.14. Machining and Finishing.** Most zinc parts are not machined, since die castings or wrought parts are formed directly in their final shape. When machining is necessary, it is easily done, especially if the tools are correctly ground.

Wrought zinc can usually be soldered with soft solder. The die casting alloys, however, are difficult to solder because of the coat of aluminum oxide. If die castings require soldering, it should be done to

an insert of copper or brass in the casting, or the part should be nickel plated.

Zinc alloys are plated or painted for decoration as well as protection. The surface preparation is of greatest importance in obtaining an adherent coat. Some finishes are baked on, but temperatures above 250 F (recrystallization temperature) are seldom used.

#### NICKEL AND NICKEL ALLOYS

**5.15. Characteristics of Nickel.** Nickel is a tough, silver-colored metal with about the same density as copper, but with three times its cost. The properties for which nickel is distinguished are oxidation and corrosion resistance, especially at high temperature, and the ability to form many alloys. Large quantities are used as an alloying element in steel and in copper alloys. The applications for nickel, and the approximate percentage of the annual production used in each, are listed in Table 5.3.

TABLE 5.3.<sup>1</sup> USES OF NICKEL IN THE UNITED STATES

<i>Application</i>	<i>Per Cent</i>
Alloy steels and cast irons	63
Copper-nickel alloys	16
Rolled nickel (including coinage)	9
Nickel plating	6
Bimetals, electrical resistors	3
Miscellaneous	3

<sup>1</sup> Data from Metals Handbook, 1939, American Society for Metals.

Although pure nickel and alloys high in nickel are used in small quantities, it would be difficult to do without them entirely. Their excellent properties persist even at high temperatures where many other metals become weak or plastic and oxidize rapidly. The oxidation of nickel usually is not dangerously rapid below 1200 to 1400 F, and many nickel parts are operated in even hotter oxidizing atmospheres. At 1800 to 2200 F, however, nickel is subject to a peculiar intercrystalline brittleness if exposed to oxidizing or sulphurizing gases. The pores of the surface grains are oxidized or sulphurized, producing a brittle surface layer which cannot be deformed by subsequent drawing or forming operations. The presence of fine surface cracks indicates that the atmosphere during heating was unsatisfactory. Where the metal must, in service, withstand such high temperatures and oxygen or sulphur atmospheres, impure grades of nickel, containing up to 5 per cent manganese, are used.

At normal temperatures nickel is ferromagnetic; however at 780 F and above it becomes paramagnetic. Many of the applications classed as miscellaneous in Table 5.3 involve the ferromagnetic properties of nickel and its alloys. Some of the nickel alloys are used for their high potential field strengths, some for their high permeability, and some for their high coercive force. They are discussed in Chapter VIII.

**5.16. Nickel Alloys.** *Monel.* The most important of the commercial nickel alloys is Monel metal, which is produced directly by removing impurities from a natural ore, and is consequently cheaper than pure nickel. Monel has the average composition 67 per cent nickel, 28 per cent copper, and 5 per cent iron, manganese, and silicon combined.

The resistance of Monel to steam attack at high temperatures has caused its extensive use in steam valves and turbine blading. Such parts may be subjected to severe erosion by unsaturated steam in which the drops of water may be traveling at velocities as high as 1000 ft per sec. Few materials are capable of enduring the impact of these drops as well as Monel. It is suitable for use in steel machinery which operates over a wide temperature range since the thermal expansions of Monel and steel are approximately equal. Where steel shafting does not have the required resistance to corrosion, Monel may be used instead; it has wear resistant qualities as good as steel if used with the correct bearings.

Monel has the best resistance to weakening at high temperatures of all the structural nonferrous metals. At 750 F it retains 75 per cent of its room temperature tensile strength, proportional limit, and elongation, and its modulus of elasticity is changed very little. At 800 F, recrystallization begins but full annealing cannot be expected below 1200 F, and even then the annealing time is too slow to be commercially useful. Monel resists oxidation at 1350 F, but it is not recommended for use above 1450 F, since nickel is superior at such temperatures.

The color of Monel is very nearly the same as that of nickel; this property together with its lower cost and corrosion resistance has brought about its use in kitchen utensils and appliances, and in laundry and dairy machinery.

K-Monel<sup>1</sup> has the same composition as Monel, except that it contains 2 to 4 per cent added aluminum. It can be hardened by precipitation heat treatment, and it has good corrosion resistance and strength at high temperature.

H-Monel<sup>1</sup> and S-Monel<sup>1</sup> are made by adding 3 and 4 per cent silicon, respectively, to Monel. They have good casting characteristics and can be hardened by precipitation heat treatment. S-Monel is very

<sup>1</sup> Designations used by the International Nickel Company.

hard and does not gall; and because of its wear resistance, it is used in cast pistons, bearings, and valve seats.

Monel can be made easy to machine by addition of 0.35 per cent sulphur. This free machining alloy is called R-Monel.<sup>1</sup>

*Inconel.* Inconel is an alloy of 80 per cent nickel, 14 per cent chromium, and 6 per cent iron. It has extremely good resistance to oxidation and corrosion in some applications, and has an impact strength better than that of any of the steels.

*Alloys with Special Mechanical Properties.* Alloys containing 30 to 40 per cent nickel with iron are known as Invar, and are characterized by extremely small coefficients of thermal expansion. They are used in length standards, in measuring tapes, and for the low expansion element of bimetal thermostats. An alloy containing 36 per cent nickel has the lowest thermal expansion of the group and is used as a length standard by the International Bureau of Weights and Measures. An alloy with the same composition except for the addition of 4 to 5 per cent chromium and 1 to 3 per cent tungsten is Elinvar. It has a nearly constant modulus of elasticity with changing temperature, and is used principally for watch springs and precision instruments.

Pure nickel is also used in bimetal thermostats, but it is used as the high-expansion element of the pair. Many other nickel alloys are used in bimetals, because of their range of expansion coefficients and because of their moderately high operating temperatures.

Wire leads for glass vacuum tubes must have a special thermal expansion coefficient to match that of the glass, in order that a gas-tight seal may be maintained and that excessive stresses will not be set up within the glass during heating and cooling. The various kinds of glass have different coefficients of thermal expansion, and so different lead-in alloys are used. The common alloys of industry contain 13 to 48 per cent nickel, depending upon the expansion coefficient desired. Wonico, Kovar, Fernico, Fernichrome, and Platinite are trade names of alloys in order of increasing nickel.

*Alloys with Special Electrical Properties.* Nickel alloys which have high electrical resistivity make ideal electric heater materials. Their characteristic resistance to complete oxidation and retention of strength at high temperatures recommends them for use at red heat. Typical standard malleable heater materials are 80 per cent nickel, 20 per cent chromium (Nichrome IV) and 60 per cent nickel, 15 chromium, 25 iron (Nichrome). There are many variations, but all aim at higher resistivity, higher operating temperature, or both. Heavy cast resistors intended for high rates of heat dissipation are made from an alloy of approximately 20 per cent chromium, 35 to 70 per cent nickel, the

remainder iron. The amount of nickel in the alloys is determined by the severity of the service. Alloys high in nickel will stand higher temperatures but are more expensive. Alloys with low thermal coefficients of resistance are used for precision electrical resistors. Constantan (45 nickel, 55 copper) and similar nickel-copper alloys have low thermal coefficients of resistance combined with fairly high resistivity.

*Fabrication.* The casting of nickel and its alloys requires some special technique since they are poured at a high temperature (about 3350 F for Monel). Forging and hot working are done successfully but the furnace in which heating is done must have a well controlled atmosphere in order to prevent the intercrystalline embrittlement caused by oxygen and sulphur. Cold working and machining of nickel and its alloys require procedures and tools similar to those used for alloy steels, although machining is done at lower cutting speed and cold working may require more power. The precipitation hardening alloys are usually machined while soft. Welding procedure is also similar to that for steel, and all the common welding methods may be used.

### LEAD AND ITS ALLOYS

**5.17. Properties and Uses of Lead.** Lead occurs in many minerals, and is relatively easy to refine and work. It was one of the first metals to be used in ancient ornamentation and industry. The Romans used it extensively, and some of the cast lead pipes they installed in England 1900 years ago are still being used.

As would be expected, the cost of lead is low, being less than zinc and less than half that of copper. Commercially, it is available in four grades.

*Antimonial lead* contains an average of about 6 per cent antimony. It is used principally in manufacture of storage batteries.

*Corroding lead* is a lead of about 99.99 per cent purity which is used by "corroders" in the manufacture of white lead, a high quality paint pigment.

*Common lead* is of somewhat lower purity than corroding lead and is used where very high purity is not necessary.

*Chemical lead* is mined in southeastern Missouri and contains 0.04 to 0.08 per cent copper. The copper improves the resistance to corrosion by certain chemicals, and has led to the use of this grade in the chemical industry.

The quantity of lead used in the typical applications is listed in Table 5.4.

The alloy of lead with antimony is of particular importance because with up to 2.4 per cent antimony it can be hardened by precipitation

heat treatment. Alloys containing up to 1 per cent antimony are used for cable sheathing. With up to 12 per cent antimony these alloys have excellent casting characteristics, but in making intricate storage battery grids, up to 0.25 per cent tin is often added to improve fluidity. These lead rich alloys containing antimony also make satisfactory bearings for slow moving machinery, and they are the cheapest of all bearing materials.

TABLE 5.4.<sup>1</sup> USES OF LEAD IN THE UNITED STATES

<i>Application</i>	<i>Per Cent</i>
Storage batteries	23
White lead, red lead, and litharge	17
Cable covering	17
Building	9
Ammunition	7
Foil	4
Solder	3.5
Bearing metal	2.5
Type metal	2
Miscellaneous	15

<sup>1</sup> Data from Metals Yearbook, 1941, U. S. Department of Interior, Bureau of Mines.

The most important lead-base bearing alloys contain both antimony and tin. The antimony combines with tin to form hard grains of the solid solution Sb-Sn in the relatively soft lead matrix. The hard particles imbedded in a soft matrix represent a condition typical of many bearing materials. The friction of the shaft sliding past the hard particles is a minimum, and yet at the same time misalignment of the shaft will distort the soft base metal so that a hard bearing surface will be form-fitted to the shaft. In lead-tin-antimony bearings, the useful range of antimony is 10 to 15 per cent. The range of tin is a great deal wider, however, ranging from practically zero to 20 per cent. The addition of tin improves the load capacity of the bearing but at the same time makes the alloy more expensive. When tin and antimony quantities are high, the Sb-Sn crystals tend to float to the top in casting. To prevent this *segregation*, up to 2 per cent of copper or arsenic is sometimes used.

## TIN

**5.18. Industrial Uses of Tin.** Tin is the most important metal which is not mined in North America. The United States has, however, imported about half the world's supply of tin, chiefly from the Orient.

It is expensive, costing about four times as much as copper, but its resistance to food corrosion has led to the exclusive use of pure tin as a plating for food containers. The plating is accomplished by hot dipping machines in which a strip of low carbon steel is run into the molten tin after passing through a zinc chloride flux, and is withdrawn from the tin through palm oil or a mineral oil substitute, which tends to equalize the thickness of the coat. A similar tinning treatment is given to copper wire in order to make it easy to solder or to prevent corrosion by various compounds present in insulations.

The relative quantity of tin used in other applications is compared with the quantity used in plating in Table 5.5.

TABLE 5.5.<sup>1</sup> USES OF TIN IN THE UNITED STATES

<i>Application</i>	<i>Per Cent</i>
Tin plate and tinning	48
Solder	21
Bronze and brass	8
Babbitt	7
Collapsible tubes	3
Foil	3
Miscellaneous	10

<sup>1</sup> Data for year 1939, Minerals Yearbook, 1940, U. S. Department of Interior, Bureau of Mines.

Solders, which rank second in use of tin, are discussed in Chapter XVI. The use of tin in bronze (phosphor bronze) and brass has been discussed in this chapter.

*Babbitt* is the name applied to the tin-base bearing metals. They are essentially alloys of tin, antimony, and copper, to which up to 30 per cent lead has been added in order to reduce the cost. The basic composition of Babbitt is usually in the range 80 to 95 per cent tin, 2 to 10 per cent copper, 2 to 10 per cent antimony. The hard solid solution Sb-Sn forms in Babbitt in very much the same way as it does in the lead-base alloys. The tin base is superior to lead, however, under severe service conditions or heavy loading. The amount of lead which can successfully be added to the alloy is limited by the severity of service.

#### SILVER

**5.19. Industrial Uses of Silver.** The use of silver in industry has expanded very rapidly during the last few years. For many centuries silver was used for ornament and for coinage, and remained a relatively scarce metal. Within the past 50 years, however, modern mining

methods and the production of silver as a by-product in mining other metals have brought a very large quantity of silver to the market. The price is still high, about 40 times that of copper, but nevertheless industrial uses in the United States account for about one-fourth of the world's supply.

The high conductivity and excellent corrosion resistance of silver are good reasons for its use in electrical contacts. Although the oxide which forms on the surface has a high resistance, it breaks down and forms metallic silver under the influence of the arc heat. This instability is one of the principal advantages of silver contacts. One of their disadvantages is softness and low melting point, and silver contacts may stick if arcing is great. Large currents are therefore not broken by opening silver points. Instead, silver is used in the form of small buttons which can be fastened to a backing of cheaper material. Where the contact must withstand considerable impact and abrasion, sterling silver (7.5 per cent copper) or coin silver (10 per cent copper) may be used. Although their strength and hardness are better than those of pure silver, they have lower conductivity and corrosion resistance.

Alloys of silver have been used in soldering and brazing because of their high strength and corrosion resistance (see Chapter XVI). Silver has even been added to heavy duty bearing metals with improvements in strength and resistance to vibration.

**5.20. Conclusion.** The foregoing discussion of each of the nonferrous metals has been intended as a general summary of the facts important in designing to use each of these metals. When a material must be selected, this general information should narrow the field to a group of metals or alloys which meet the requirements. To determine the one metal or alloy which is best, however, may often require a knowledge of facts which have not been presented here. The physical properties of the hundreds of nonferrous alloys may best be obtained from design handbooks or from manufacturers' specifications. The designer should also determine the current cost of the material, as well as the fabricating cost, and compare these with the costs for other metals.

#### REVIEW QUESTIONS

1. How do copper, aluminum, magnesium, zinc, and their alloys compare with plain low-carbon steel in (a) magnetic properties, (b) melting point, (c) electrical and thermal conductivity, (d) tensile strength, (e) modulus of elasticity, and (f) base cost of metal?
2. (a) Name the three grades of commercial copper and tell how they differ in composition. (b) Where strength is important, which would be used for a cold drawn wire which is to be soldered? For a part to be gas welded?

3. (a) Which brasses are best adapted to cold working and which to hot working?  
(b) Under what conditions can cartridge brass (30 Zn) be both hot and cold worked successfully?
4. Brass is subject to two characteristic kinds of corrosion. Name these and the types of brass most susceptible to each.
5. (a) Aluminum naturally has good corrosion resistance. To what characteristic of the metal is this due? (b) How does "anodization" increase the corrosion resistance? (c) Do soldered aluminum joints have good resistance to corrosion?
6. A pound of alloy steel will support a tensile load as great as can be supported by a pound of aluminum alloy, and in addition, the steel occupies less space. Yet aluminum is often used in aircraft. Give at least two reasons for its use.
7. (a) In general, how do the compositions of aluminum casting alloys differ from those of the alloys for wrought forms? (b) What are the two principal alloying elements used with aluminum, and why is each used?
8. (a) What special precaution should be observed in designing magnesium castings? (b) What special practices must be used in the foundry?
9. Give two advantages and two disadvantages of zinc alloy die castings.
10. Many nickel alloys have been developed, each to satisfy at least one specific requirement. Name at least four of these requirements.

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## CHAPTER VI

### HEAT TREATMENT

**6.1. Introduction.** The purpose of submitting metals and alloys to heat treatment is to impart to them certain desired physical properties. Usually it is also desired to preserve as nearly as possible the shape, size, and surface finish of the part being treated.

The new properties obtained are due to changes in structure. In most treatments, this involves a change in the nature, form, size, or distribution of the structural constituents. Less frequently, it involves a change in chemical composition, as in carburizing and nitriding, or a change in internal stress, such as relief of internal stress or establishment of stresses of a definite kind. A complete study of heat treatment thus involves consideration of (*a*) the structural condition of the part before treatment, (*b*) the structural changes attending the heating, holding at heat, cooling, and reheating operations, and (*c*) the structural condition permanently retained.

The structural changes in steel resulting from most heat treating operations differ markedly from those changes characteristic of most nonferrous alloys when subjected to similar treatments. It is therefore convenient to divide this chapter into separate sections for the ferrous alloys and for the nonferrous alloys. This division will facilitate discussion of the characteristic response of each group, and at the same time, should, through comparison, permit emphasis on the important differences between their heat treatments.

#### HEAT TREATMENT OF STEEL

By J. E. ERB and J. F. YOUNG

**6.2. General.** Hardening and annealing are the two fundamental operations in heat treating. Hardening may be for the purpose of increasing strength, or for improving wear resistance or resistance to indentation; annealing for softening and relieving stress. In general, the hardening operation for steel is conducted by heating the piece to a relatively high temperature, holding for a required length of time, and then cooling at a relatively high rate, as by quenching. Quenching stresses may be relieved and the hardness reduced to the desired value

by reheating (tempering) to a somewhat lower temperature. The true annealing operation generally involves heating to a required temperature and cooling rather slowly (as with furnace cooling).

The structural changes which take place in the steel during these heating and cooling operations depend on the previous thermal history, the heating and cooling rates, and the chemical composition of the

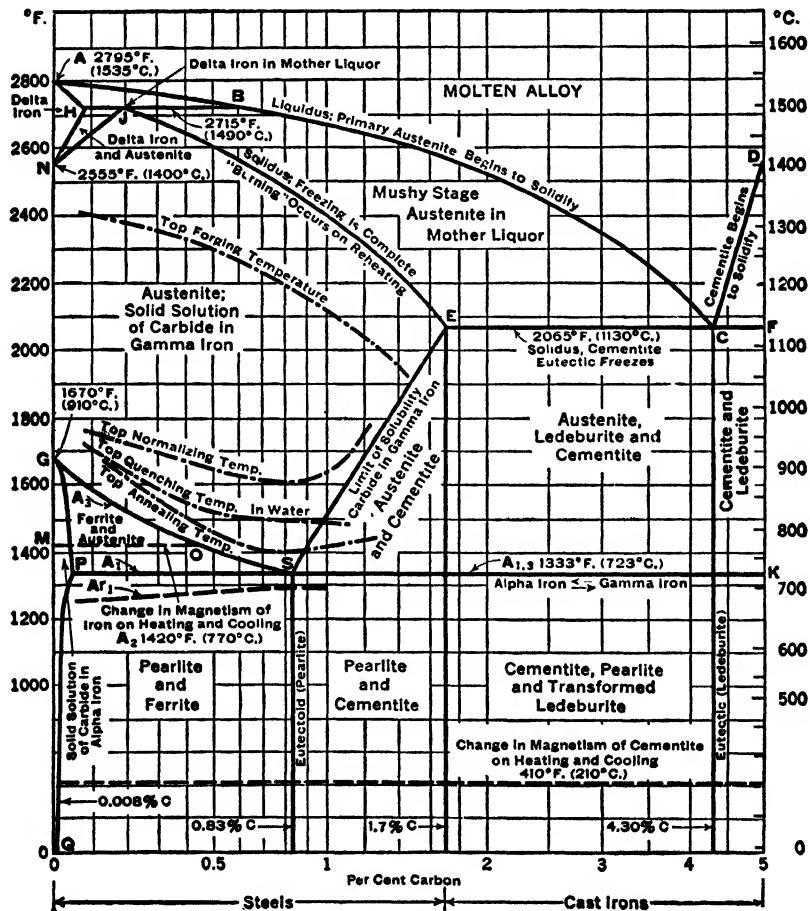


FIG. 6.1. Equilibrium diagram for the iron-carbon alloy system.

alloy. In Chapter II, the effect of heat treatment on several different iron-carbon alloys was briefly described. The equilibrium diagram for this alloy system was also introduced to furnish a basis for discussing the phase changes which take place under both equilibrium and non-equilibrium conditions. The information presented in Chapter II will

not be reviewed here, but it will be of value to reconsider the phases present in various compositions of steel and the manner in which alloying elements other than carbon are associated with these phases.

**6.3. The Structure of Steel.** Solid steel is made up primarily of one or more of the three phases, ferrite, cementite, and austenite. These are indicated on the equilibrium diagram (Fig. 6.1). Steel containing either ferrite or both ferrite and cementite, when heated above the

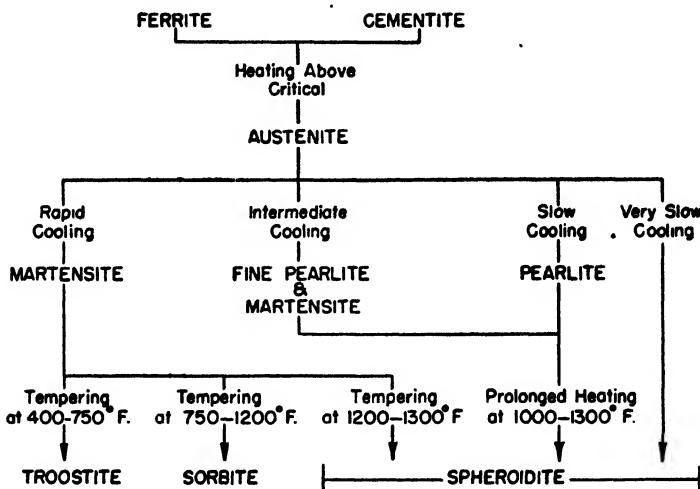


FIG. 6.2. Diagram showing the formation of the various structures of plain carbon steels. (*Adapted from The Working, Heat Treating, and Welding of Steel*, by H. L. Campbell, John Wiley & Sons, New York, 1941, p. 61.)

transformation temperature, becomes austenitic (see Fig. 6.2). Quenching the austenite at various rates, and then tempering the more drastically quenched material results in the other structures listed on Fig. 6.2. Each of these is briefly described below.

**Ferrite.** Solid solutions of which  $\alpha$ -iron is the solvent may be called ferrite (see Fig. 6.3).<sup>1</sup> It forms from the gamma (austenitic) phase in slow-cooled alloys, within the field bounded by GSP (Fig. 6.1). Unless it has been hardened by cold working, ferrite is soft (50 to 100 Brinell) and is usually ductile. It may contain in solid solution manganese, silicon, chromium, nickel, and numerous other elements, but very little carbon.

**Cementite.** Cementite is the intermetallic compound of carbon and iron,  $\text{Fe}_3\text{C}$ . It is very hard (approximately 1400 Brinell) and brittle, and appears in the annealed steel as parallel plates (lamellar layers), as rounded particles (spheroids), or as envelopes around the pearlite grains (see Fig. 6.4). This phase is formed in slowly cooled solid alloys within the field ESK. In alloy steels, it may contain, besides iron and

<sup>1</sup> All photomicrographs in this chapter are by members of the Schenectady Works Laboratory of the General Electric Company.



FIG. 6.3. Ferrite in commercially pure (Armco) iron  $\times 100$  (by E. D. Reilly).

FIG. 6.4. Spheroidal, lamellar, and boundary cementite in annealed high carbon steel  $\times 1000$  (by E. D. Reilly).

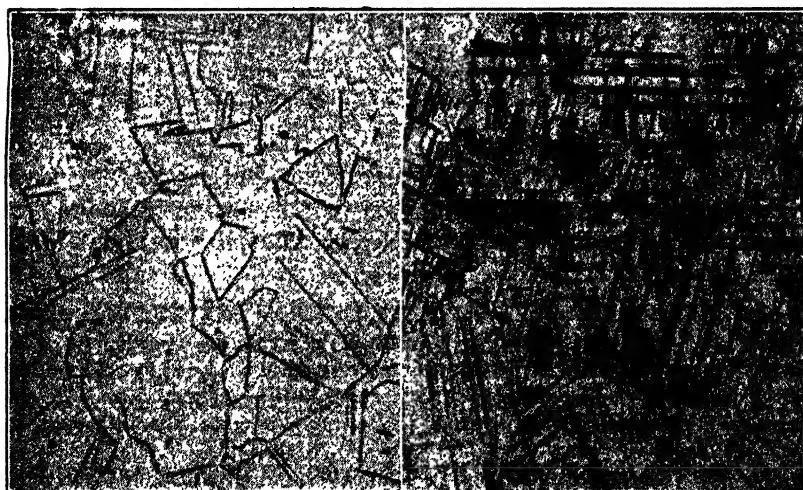


FIG. 6.5. Left, austenite in 18 Cr-8 Ni stainless steel  $\times 250$  (by E. D. Reilly). Right, austenite in "nonmagnetic" (16% Mn) cast steel  $\times 100$  (by Joyce Thomas).

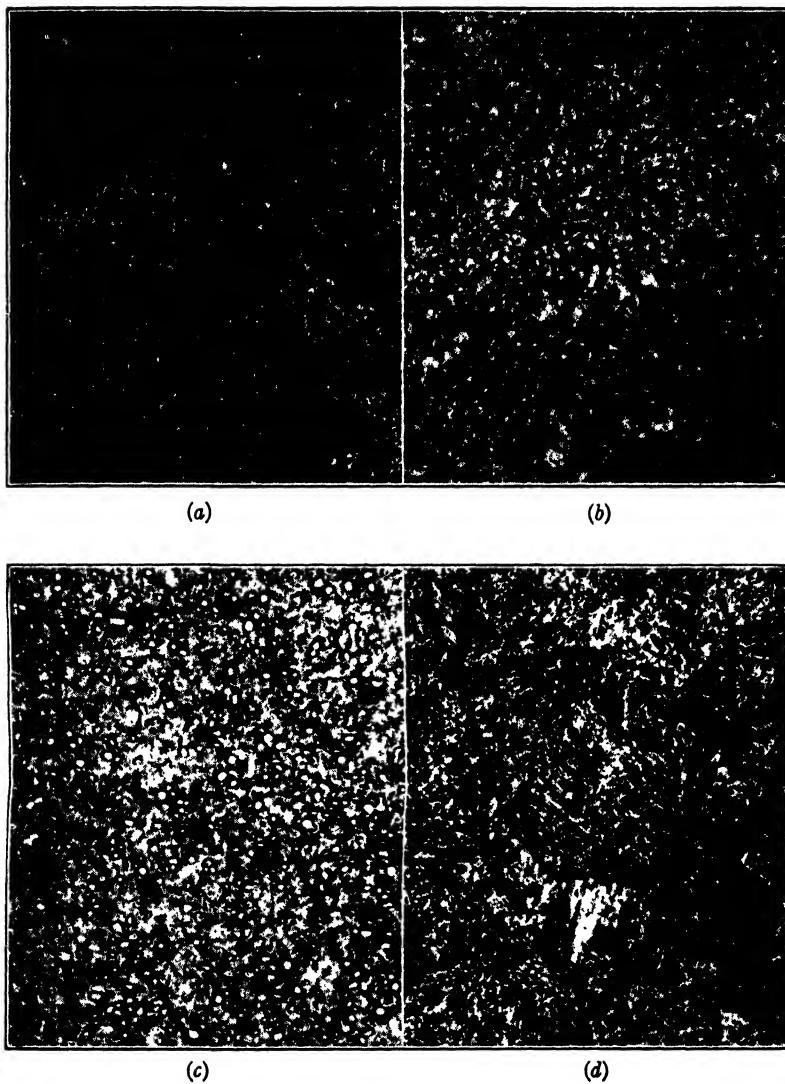


FIG. 6.6. (a) Martensite in 0.50% C steel, 700 Brinell  $\times 500$  (by E. D. Reilly).  
(b) Martensite with excess cementite in high speed steel, hardened and tempered  $\times 500$ . The white areas are cementite. (By E. D. Reilly.)  
(c) Martensite with excess cementite in 1.30% C steel safety razor blade, 800 Brinell  $\times 1000$ . The white areas are cementite. (By R. N. Gillmor.)  
(d) Martensite with excess ferrite, 500 Brinell  $\times 500$  (by J. J. Vrooman).

carbon, one or more of the added "carbide forming" elements such as chromium, molybdenum, vanadium, and tungsten.

**Austenite.** Austenite is the name given to the solid solutions of which  $\gamma$ -iron is the solvent. This solid solution can dissolve up to 1.7 per cent carbon, depending upon the temperature (see line *SE* in Fig. 6.1). It may also contain nickel, manganese, silicon, and numerous other elements in solid solution.

Obviously, austenite may exist at room temperature only when the normal  $\gamma \rightarrow \alpha$  transformation has been suppressed. Even when plain high carbon alloys are quenched very drastically, the resulting structure contains only a small fraction



(e)

FIG. 6.6. (e) Martensite and retained austenite in high speed steel, hardened but not tempered 800 Brinell  $\times 500$  (by E. D. Reilly).

of austenite. Therefore austenite rarely appears in any quantity in plain or low alloy steels. Manganese, nickel, and certain other elements are very effective in suppressing the  $\gamma \rightarrow \alpha$  transformation, and even slow-cooled alloys containing certain relatively high percentages of these elements are completely austenitic at room temperature (see Fig. 6.5). Unless cold worked, austenite is generally soft and quite ductile. At elevated temperatures the austenitic steels are stronger and less ductile than the ferritic. Austenite is also more dense than ferrite, its electrical resistance and thermal coefficient of expansion are higher, and it is practically non-magnetic (paramagnetic). Cold plastic working or chilling in liquid air will often cause "retained" austenite to transform spontaneously to *martensite*.

**Martensite.** Martensite, the principal structure in fully hardened steels, is formed in carbon steels by fast cooling  $\gamma$  solid solution (austenite) to temperatures below 450 F. It has a tetragonal crystal structure which may be considered as tetragonal ferrite greatly supersaturated with carbon. Some of the carbon may have precipitated during cooling as finely dispersed cementite among the "feathers" or "needles" of the tetragonal structure. The martensitic areas are very hard, 500 to 1000 Brinell, according to carbon content and fineness of structure. They may

contain various percentages of "retained" (untransformed) austenite and also "excess" ferrite or cementite according to the composition of the alloy and its treatment. Several photomicrographs of these combinations are illustrated in Fig. 6.6. "Retained" austenite in martensitic structure is not easily distinguished microscopically, but its presence may be established by hardness, density, or magnetic tests. Martensite is less dense than pearlite or spheroidite, owing to the metastable tetragonal lattice. Therefore an increase in volume takes place in steel when it is fully hardened.



FIG. 6.7. Pearlite in eutectoid (0.83% C) steel  $\times 1000$  (by D. B. Blackwood).

**Pearlite.** Pearlite consists of alternate layers of ferrite and cementite in the proportions 87 to 13 by weight. The areas of pearlite are formed spontaneously from slow cooling  $\gamma$  solid solution through the temperature of the line *PSK*, Fig. 6.1. A photomicrograph of pearlite is illustrated in Fig. 6.7. Note that pearlite is the *eutectoid structure* of two phases in iron-carbon alloys.

Steels containing less than 0.83 per cent carbon are called hypoeutectoid steels, and those which contain more are called hypereutectoid. This terminology applies only to plain and low alloy steels. With high alloy steels the eutectoid composition is altered and the structure may not even exist. To distinguish between the ferrite and cementite phases of the pearlite structure, the separate ferrite in hypoeutectoid steels and the corresponding cementite of hypereutectoid steels are known as "free" or "excess" ferrite and cementite respectively. Photomicrographs of pearlitic steels with excess ferrite and cementite are illustrated in Fig. 6.8. An electron micrograph of pearlite with excess cementite is illustrated in Fig. 6.9. The properties of pearlite are, of course, a composite of those of ferrite and cementite.

With faster cooling, pearlitic structure may continue to form down to temperatures of 900 F, the spacing between layers becoming finer at the lower temperatures of formation (see Fig. 6.10). The hardness increases with the fineness of this spacing, ranging from 170 to perhaps 400 Brinell.

**Spheroidite.** In this structure the cementite takes the form of rounded particles, or spheroids, instead of plates. Just as the spacing varies in pearlite so does the

size of the spheroids, as illustrated in Fig. 6.11, the finer grained material being the harder and stronger. Spheroidite is softer and more ductile than pearlite, but not as freely machinable. It may form directly from slow cooling hypereutectoid  $\gamma$  solid solution which contains undissolved excess cementite, present because the

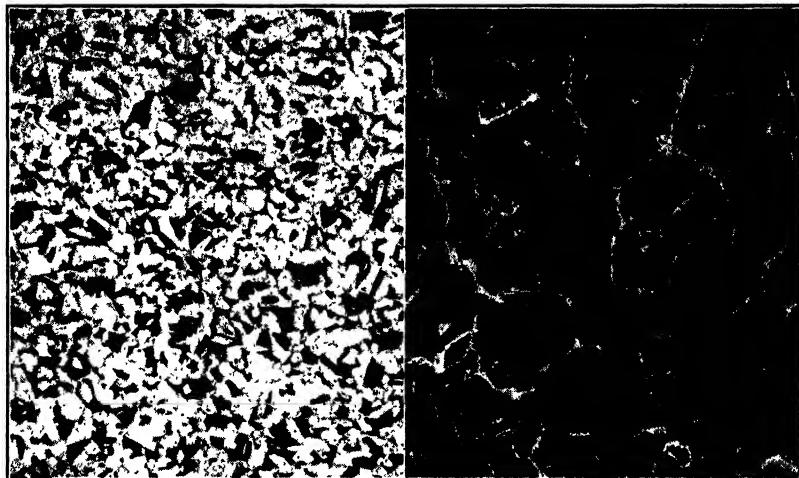


FIG. 6.8. Left, pearlite and "free" ferrite (light grains) in hypoeutectoid (0.30% C) steel  $\times 100$  (by W. G. Conant).

Right, pearlite and "free" cementite (light areas) in hypereutectoid (1.0% C) steel  $\times 100$  (by D. B. Blackwood).

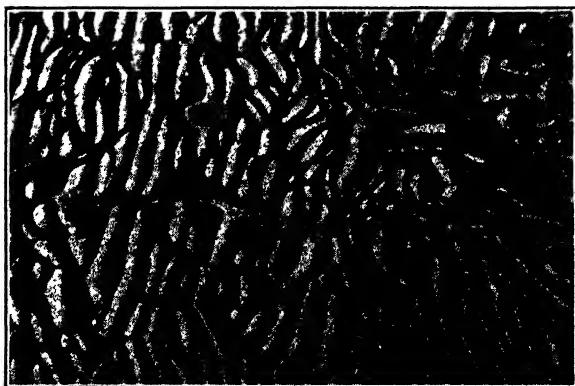


FIG. 6.9. Electron-micrograph of 1.1% C steel showing excess cementite and pearlite. The light regions are cementite.  $\times 10,000$  (original  $\times 5000$ ). (By Research Laboratory, General Electric Company.)

alloy has not been heated above the line  $SE$ , Fig. 6.1. Also, lamellar pearlite may be spheroidized by heating the steel for relatively long periods of time just below the eutectoid transformation (Fig. 6.12). Spheroidite may also be produced by

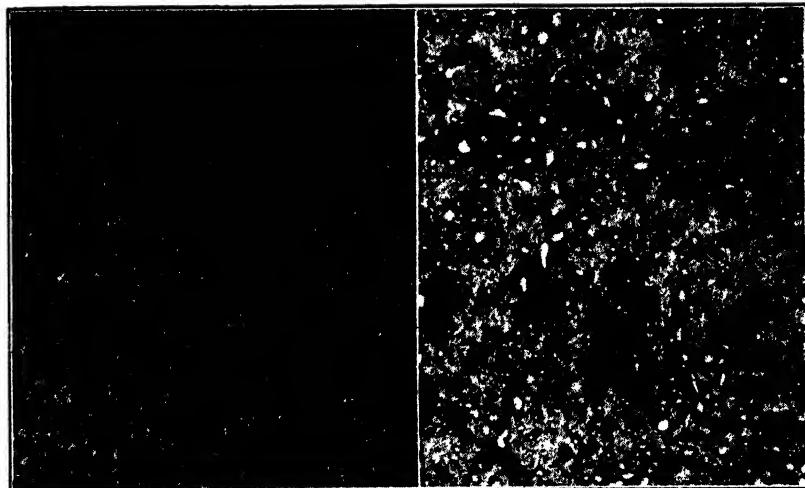


FIG. 6.10. Left, fine pearlite (dark) and martensite (light) in incompletely hardened high carbon steel  $\times 100$  (by E. D. Reilly).

Right, fine pearlite under high magnification. This structure is sometimes called "primary troostite."  $\times 1000$ . (By E. D. Reilly.)

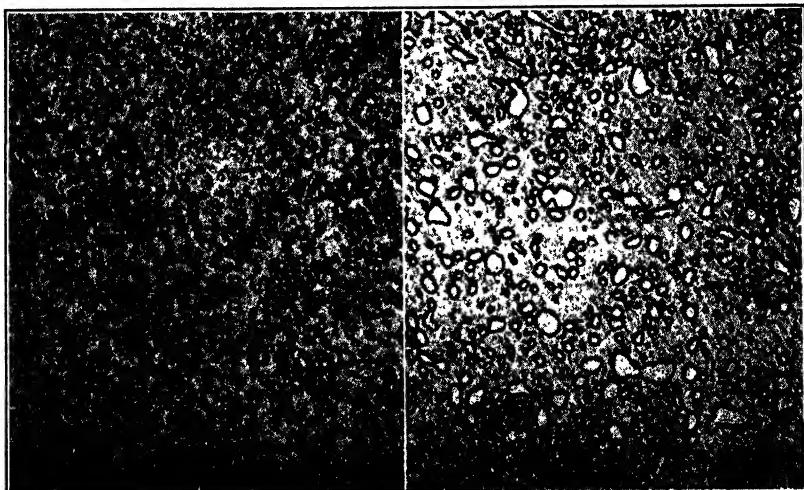


FIG. 6.11. Left, spheroidite — fine spheroids — C 0.9, Mn 2.0, Cr 2.0, Mo 1.0. Brinell 230  $\times 1000$  (by R. N. Gillmor).

Right, spheroidite — large spheroids — C 1.60, Cr 12, Mo 1.0, Va 0.25. 216 Brinell.  $\times 1000$ . (By R. N. Gillmor.)

heating martensite or the temper structures of martensite in the range just below the eutectoid transformation.

*Troostite.* If martensite is reheated (tempered) at temperatures (in plain steels) between about 400 and 750 F, a softer, more ductile structure known as troostite is formed. This structure is dark etching (see Fig. 6.13) and apparently consists of submicroscopic particles of cementite in ferrite.

The name "primary troostite" may be applied to the fine pearlite structure obtained on direct cooling and illustrated in Fig. 6.10, but the name troostite is more generally applied to this "secondary" or tempered product. Some prefer to think of the structure as tempered martensite of a measured hardness because

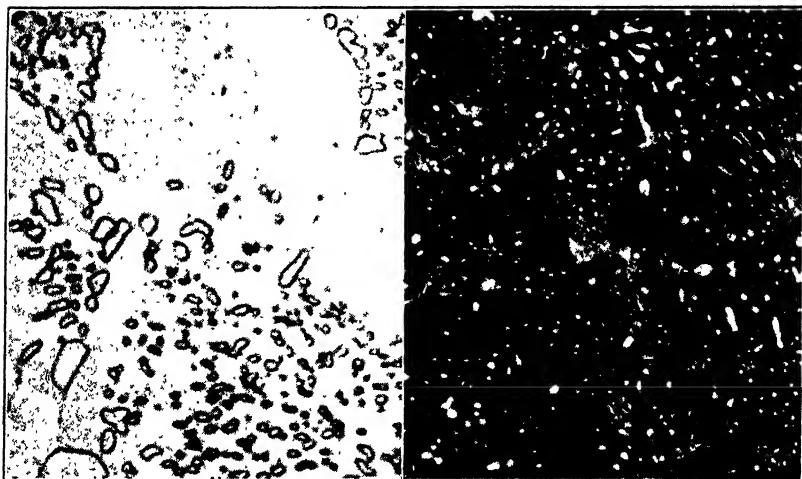


FIG. 6.12. Spheroidite in hypoeutectoid (0.20% C) steel formed from pearlite after 500 hr. at 1250 F.  $\times 1500$ . (By E. M. Eoff.)

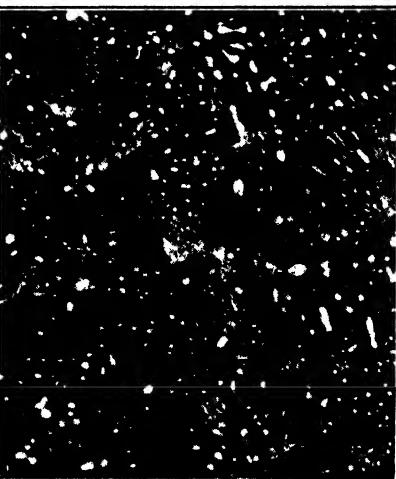


FIG. 6.13. Troostite in plain (1.10% C) steel hardened at 1475 F, quenched in brine, and tempered one hour at 550 F.  $\times 1000$ . (By E. D. Reilly.)

of the otherwise arbitrary degree of grain growth and agglomeration which may characterize the same structure.

*Sorbite.* When troostite (in plain carbon steel) is heated in the temperature range 750 to 1100 F, it changes by indistinguishable degrees into a structure known as sorbite, in which the cementite has grown until it has a distinctly granular appearance (see Fig. 6.14). It is softer and more ductile than troostite. Tempering at still higher temperatures causes continued grain growth until the cementite forms the larger spheroids characterized by spheroidite.

For the sake of completeness, the several structures and constituents of the cast irons will also be reviewed.

*Lebedurite* is the eutectic of the iron-carbide alloy system. It is designated by point C in the diagram, Fig. 6.1. White cast iron usually consists of a mixture of lebedurite and pearlite (see Fig. 6.15). By prolonged annealing (malleabilizing), some or all of the cementite is converted to graphite (temper carbon), and the resulting structure, malleable cast iron, consists of graphite "rosettes" or nodules and various amounts of ferrite and pearlite. Graphite is also present in gray cast iron,

but in this iron it forms directly during cooling in the mold and is in the form of long curved flakes. The presence of carbon as graphite instead of in cementite is promoted by high carbon and silicon contents. Photomicrographs of irons are illustrated in Chapter IV.



FIG. 6.14. Sorbite in plain (1.10% C) steel hardened at 1475 F, quenched in brine, and tempered one hour at 1000 F.  $\times 1000$ . (By E. D. Reilly.)



FIG. 6.15. Left, ledeburite, the eutectic of Fe-Fe<sub>3</sub>C, in white cast iron  $\times 500$  (by N. J. Gendron).

Right, eutectic in high speed steel weld deposit. The "skeleton" or "feathery" material is the eutectic resembling ledeburite.  $\times 600$ . (By D. B. Blackwood.)

**6.4. The Transformation of Austenite.** The influence of carbon on the  $\alpha \rightleftharpoons \gamma$  transformation temperature is shown on the equilibrium diagram, Fig. 6.1. The beginning of the transformation on heating is indicated for the various alloys by line *GPSK*, ( $A_1$ ), and the end by line *GSK*, ( $A_3$ ). Even for slow heating and cooling at rates customary in heat treating, the temperature at which the transformation begins and ends is displaced from  $A_1$  and  $A_3$ . Lines indicating the displaced transformation temperature are designated by subscripts<sup>1</sup> *r* and *c* for cooling and heating respectively.  $A_{r1}$  is included in Fig. 6.1.

**Change in Density.** The  $\alpha \rightarrow \gamma$  transformation is accompanied by an increase in density because of the "closer packing" of atoms in the face-centered  $\gamma$  lattice (at 1670 F, the densities of the phases are  $\alpha = 7.54$  g/cc, and  $\gamma = 7.63$  g/cc). The  $\gamma \rightarrow \alpha$  change shows a corresponding decrease in density.

Volume changes are measured by an instrument called a dilatometer which records changes in length with temperature. This instrument has been invaluable in determining the transformation temperatures for various steels. The three dilatometer curves in Fig. 6.16 show how the temperature of transformation is affected by the rate of cooling.

**Rate of Cooling.** Annealing is slow cooling under practical equilibrium conditions, thus allowing the  $\gamma \rightarrow \alpha$  transformation to occur at high temperature (1300 F), favorable to the development of large grain size, and of equilibrium structures of ferrite, pearlite, and cementite as determined by composition.

Conversely, rapid cooling causes hardening because (a) the transformation is lowered to a temperature (below 450 F) favorable to the formation of the finest possible grain size, (b) the normal  $\alpha$ -lattice may not have time to form, and (c) the carbides hardly have time to form, let alone coalesce, and therefore are fixed in a metastable state approaching critical size and dispersion.

Intermediate rates of cooling may cause a "split transformation," that is, part of the action takes place at an intermediate temperature, say 1000 F, and the rest at the lower temperature, around 450 F.

**Time-Temperature-Transformation Curves.** These reactions, particularly the latter, may be better understood from the time-temperature-transformation curves (sometimes called S-curves) developed by Davenport and Bain.<sup>2</sup> These curves for any particular steel are developed as follows. Samples of the steel are heated to a temperature

<sup>1</sup> The subscripts *r* and *c* come from the French words refroidir and chauffer, which mean recooling and heating, respectively.

<sup>2</sup> See "The Transformation of Austenite at Constant Subcritical Temperatures," by E. S. Davenport and E. C. Bain, *Trans. A.I.M.M.E.*, Vol. 90, pp. 117-144, 1930.

above the critical and are then quenched in a molten bath which is held at a constant subcritical temperature. After holding at this point for the indicated time, the sample is quenched quickly to room temperature. The extent of transformation at the holding temperature is

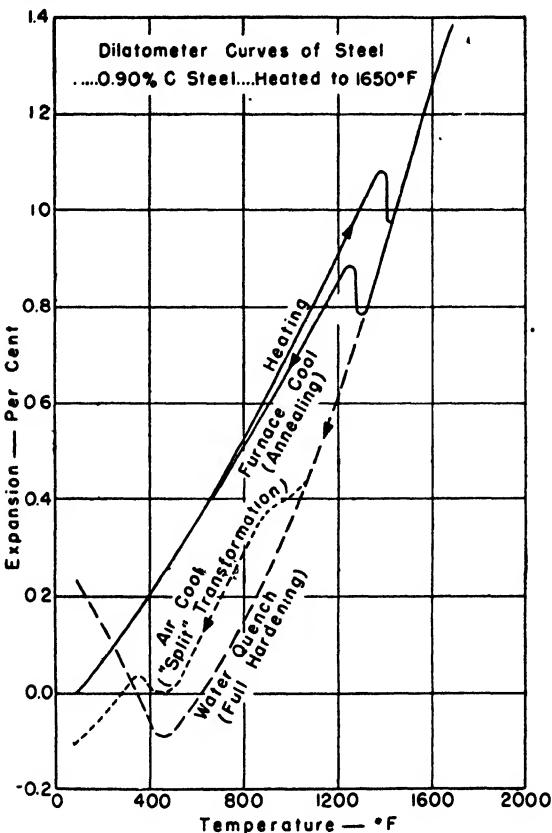


FIG. 6.16. Dilatometer curves of 0.9% C steel, heated to 1650 F and cooled at three different rates.

determined by microscopic examination, or by hardness test. Full hardness would indicate that martensitization had taken place, whereas a lower hardness with shorter time would indicate some retained austenite and, with longer time, progress in structural change toward the pearlitic form as the upper limit.

These experiments are continued on different temperature levels, varying the holding time as indicated, until sufficient data are established to plot the beginning and the end of transformation at all temperatures, thus forming the  $T-T-T$  curves. Fig. 6.17 shows these

curves for a 0.78 per cent plain carbon steel. Their general shape is the same for all steels but of course the individual features will vary according to the particular composition.

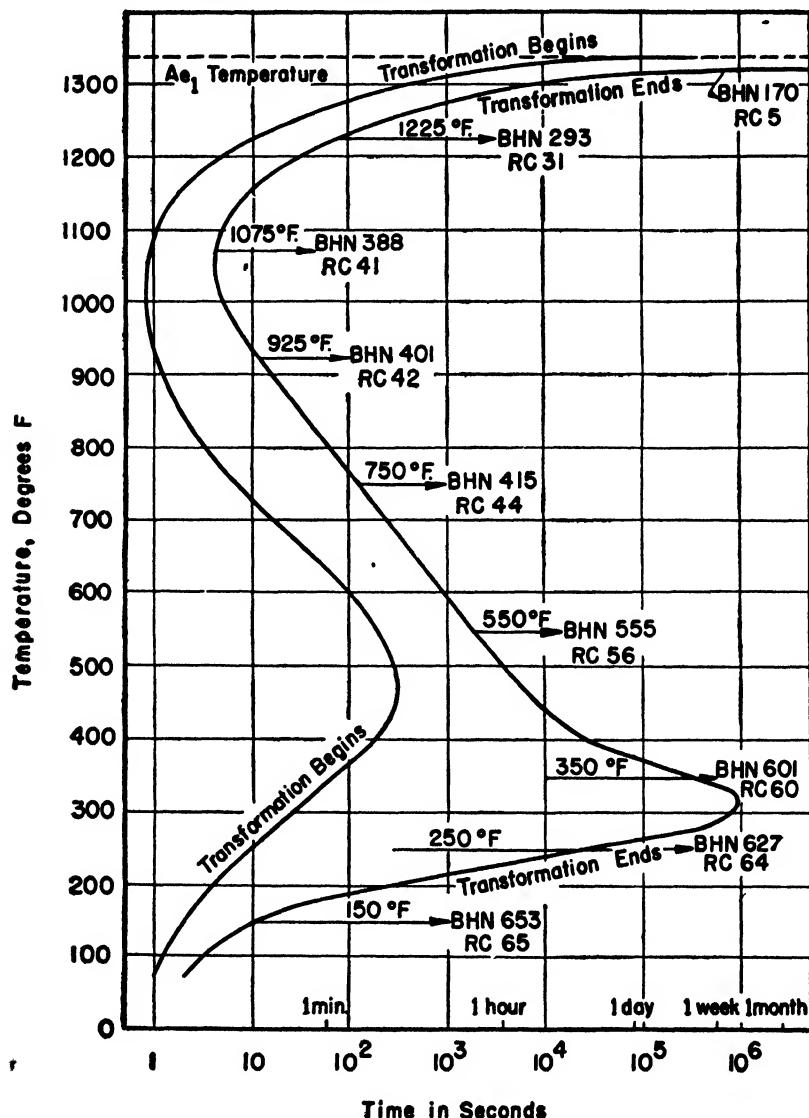


FIG. 6.17. *T-T-T* curve for 0.78% C steel.

***T-T-T Curves and Cooling Rate.*** Such curves are extremely useful as a guide to the heat treatment of a particular kind of steel since they

permit prediction of the structure and properties which result from a given cooling cycle. All that is necessary is to superimpose the cooling curve on the  $T-T-T$  curve, as in Fig. 6.18. Curve *A* may be taken to represent a water quench — extremely rapid cooling. The point where it crosses the first  $T-T-T$  curve corresponds with the start of the transformation. The intersection with the second  $T-T-T$  curve corresponds with the end of the transformation. Full hardening therefore takes place. Compare with the dilatometer curve, Fig. 6.16, for a water quench.

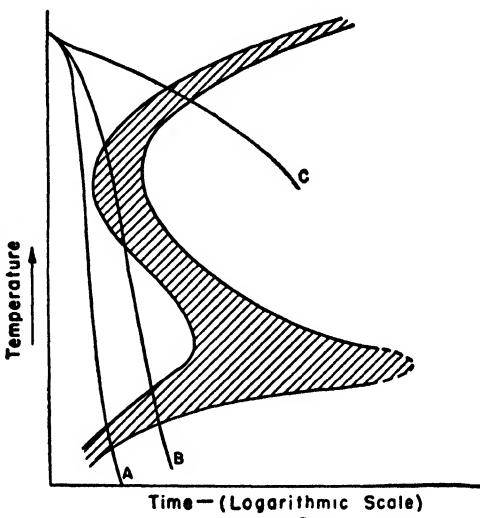


FIG. 6.18.  $T-T-T$  curve and three cooling curves.

Cooling curve *B* could represent air cooling, for example. Here a mixture of structures might be expected because some of the grains transform at the "knee" of the curve, the product being "fine pearlite," while others wait until they cross the "toe" of the curve and consequently develop martensite. Compare this with the dilatometer curve for air cooling, Fig. 6.16.

Curve *C* might represent slow cooling in a furnace, yielding true pearlite or spheroidite.

*Interrupted Quenching.* For all practical purposes, the space between the knee and the vertical axis may be looked upon as a "gate"<sup>1</sup> through which the steel must pass in a given time (about 0.9 sec. for 0.78 carbon steel in Fig. 6.17) in order to harden. But below the knee, considerable

<sup>1</sup> A term coined by H. C. McQuaid.

time may elapse before hardening begins. This permits an interrupted quench. That is, if the heat treater receives a part which is certain to crack if it is quenched in water, he may start the quench with water and end up with oil. Long slim objects such as shafts may be quenched to a point below the knee, say 500 F, and then straightened while the steel is still relatively plastic, before the hardening reaction sets in.

Isothermal hardening cycles ("patenting," "austempering") may be established from the  $T-T-T$  curve. That is, the steel may be quenched into a molten bath which is maintained at some constant temperature, say 700 F. It is kept in this bath long enough for hardening to take place. This reduces the danger of cracking which might be caused by a drastic water quench, particularly if the steel is coarse-grained or in an otherwise sensitive condition.

By quenching certain parts made from oil-hardening steels in a molten salt bath at 350 F, warpage and cracking have been reduced about 50 per cent. Isothermal annealing, also indicated by the  $T-T-T$  curve, has certain advantages over old-style furnace cooling.

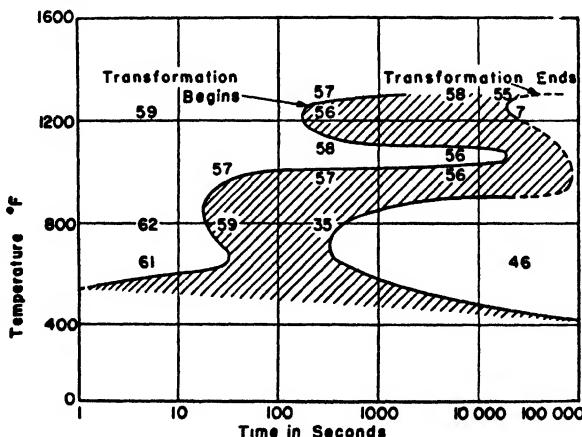


FIG. 6.19.  $T-T-T$  curve for chromium-molybdenum-nickel (SAE 4340) steel. Numbers indicate Rockwell C. hardness.

**6.5. Hardenability and Quenching.** The foregoing considerations lead naturally to the conception of hardenability. Hardenability is defined here as the ability of a given steel to develop its maximum potential hardness with respect to the time of cooling. That is, a steel of high hardenability would develop full hardness with relatively slow cooling. Fig. 6.19 is a  $T-T-T$  curve for SAE 4340, a steel of high hardenability. Note that the width of the gate for this steel is about 20 sec.,

compared to less than 1 sec. for the 0.78 per cent plain carbon steel. This alloy steel will therefore harden with much slower cooling.

Hardenability may also be conceived as the depth that the hardened zone penetrates into a piece of given size. Fig. 6.20 shows this effect

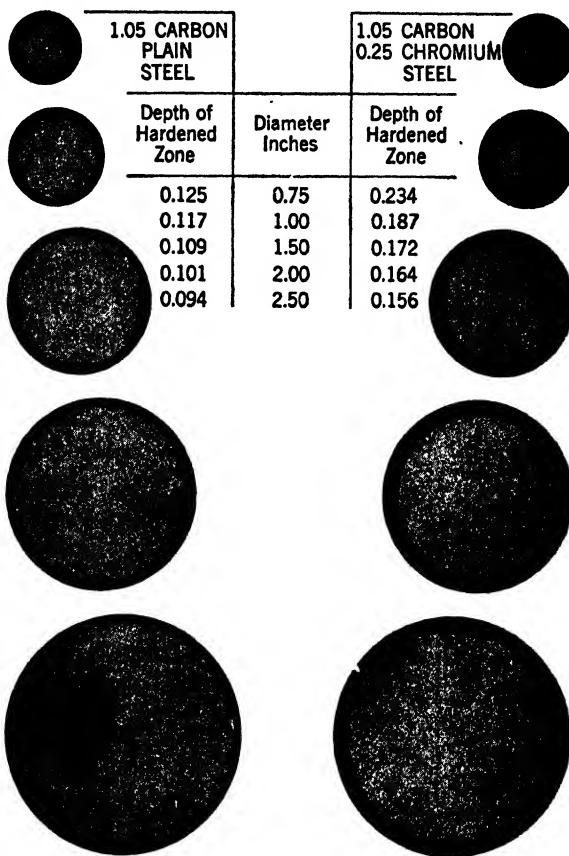


FIG. 6.20. Relative hardenability of plain carbon steel and chromium-bearing steel of the same carbon content. (*Courtesy Crucible Steel Co. of America.*)

on two steels of approximately 1.05 per cent carbon. The chromium-bearing steel on the right has the greater hardenability. Note the sharp line separating the hardened from the unhardened zone. The Brinell hardness of the surface layer is about 890 and of the core about 390, a difference of 500 points Brinell. The dark colored outer shell is composed of martensite which has formed according to curve *A*, Fig. 6.18, while the core, a mixture of fine pearlite and martensite, developed according to curve *B*.

**6.6. Jominy Tests for Hardenability.** In the Jominy test for hardenability of steel, a sample approximately 1 in. in diameter and 4 in. long is heated to the proper temperature and then quenched on one end by means of a standardized "fountain" of water, as illustrated in Fig. 6.21. This produces very rapid cooling on the quenched end, with progres-

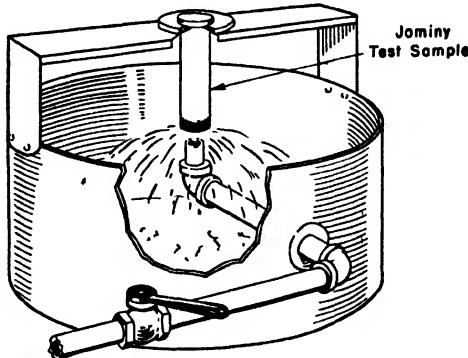


FIG. 6.21. Sketch of Jominy end-quenching operation. (*Courtesy Joseph T. Ryerson & Sons, Inc.*)

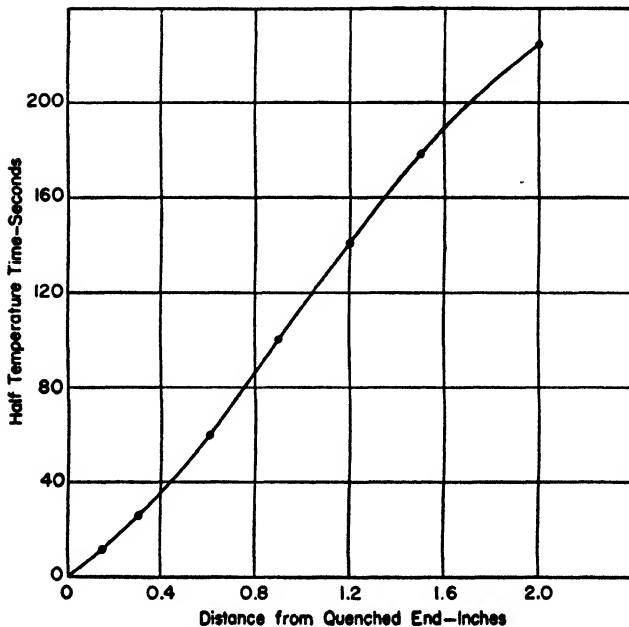


FIG. 6.22. Cooling rates on a Jominy test bar expressed as half temperature time. (*From "Correlation between Jominy Test and Quenched Round Bars," by Asimow, Craig, and Grossman.*)

sively slower cooling along the bar. The rates of cooling at different points have been carefully determined and are given in Fig. 6.22. They are expressed as the "half temperature time," i.e., the number of seconds for the temperature to be halved.

After quenching, two flats are ground lengthwise on the bar, and indentation hardness readings taken at measured distances from the quenched end (see Fig. 6.23). Comparison of these readings with the rates of cooling given in Fig. 6.22 makes it possible to ascertain the hardness that would be obtained in a section of a part made of the same material and cooled at some specified rate. Conversely, if the hardness of the material of some part is known, the cooling time can be determined by reference to Jominy tests for the material. It is also possible to select a material on the basis of these tests which will have the proper gradient of hardness for the cooling times given by a quench, e.g., in water or oil, by plotting the desired Jominy hardness curve and comparing it with the curves for the available alloys.

Curves<sup>1</sup> are now available whereby the cooling time of different steel sections can be calculated. After some 2000 years of practice, the heat treatment of steel has at last been established on a quantitative basis.

**6.7. Effect of Alloying Elements on Hardenability.** During the past quarter century, the rapid development of alloy steels tended to obscure the fact that *carbon* is after all the primary hardening element in steel. Numerous investigations have established beyond question that the "potential" maximum hardness of steel depends solely upon carbon, being practically unaffected by alloys. The only proviso is that the steel must be cooled *fast* enough. Alloys do increase hardenability, that is, the ability to develop a given hardness with slower cooling. It is also true that the minimum (annealed) hardness is affected to some degree by the solid-solution effect in alloys.

Besides carbon, the principal alloying elements used in steel are:

<sup>1</sup> See curves from T. F. Russell, published in "The Flow of Heat in Steel," by J. B. Austin, Am. Soc. Metals, 1941.

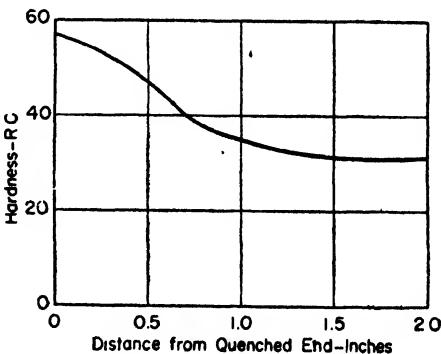


FIG. 6.23. Jominy hardness for NE 9440 alloy steel. (Courtesy of Joseph T. Ryerson & Sons, Inc.)

manganese, silicon, chromium, molybdenum, vanadium, tungsten, nickel, cobalt, sulphur, and phosphorus. Their effects on hardenability are summarized on the following curves prepared largely from data by Grossmann,<sup>1</sup> French,<sup>2</sup> Digges,<sup>3</sup> and Esser.<sup>4</sup>

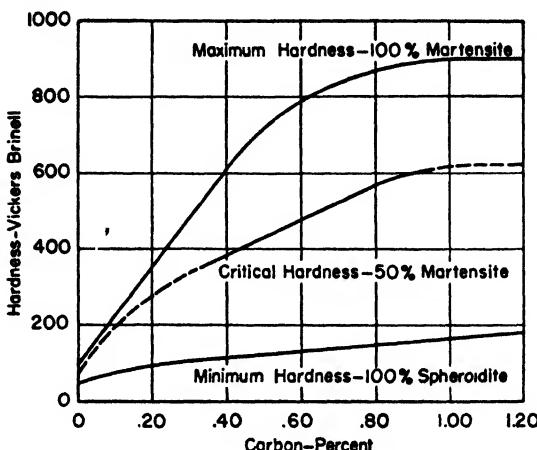


FIG. 6.24. Relation of carbon to the hardness of steel.

Fig. 6.24 shows the relation of carbon to the hardness of steel. The two upper curves, which indicate hardness for 100 per cent and 50 per cent martensite, are practically unaffected by alloy content. The lower curve for spheroidite is only slightly affected. Note that for low carbon content, the increase in hardness is small, even for the most drastic quench. This explains why, with the exception of carburizing and the annealing of cold worked material, low carbon steels are seldom heat treated.

The relation of carbon to the hardenability of pure iron-carbon alloys, expressed as the minimum half temperature quenching time to develop "critical" hardness (i.e., for 50 per cent martensite of same carbon content), is shown in Fig. 6.25. All the curves show that hardenability increases with carbon content up to about 0.9 per cent, since the rate of cooling to develop the specified hardness decreases. For higher carbon

<sup>1</sup> Grossmann, M. A., "Hardenability Calculated from Chemical Composition," *Am. Inst. Mining Metal Engrs., Tech. Pub. 1437*, June 1942.

<sup>2</sup> French, H. J., "The Quenching of Steels," *Am. Soc. Steel Treating (Am. Soc. Metals)*, Cleveland, 1930.

<sup>3</sup> Digges, T. G., "Effect of Carbon on the Hardenability of Pure Iron Carbon Alloys," *Am. Soc. Metals Trans.*, 1938, p. 408.

<sup>4</sup> Esser, H., W. Eilender, and H. Majert, "Archiv fur das Eisenhuttenwesen," Vol. 7, pp. 367.

content, the hardenability is reduced. The numbers on these curves refer to grain size according to the ASTM system.<sup>1</sup> The larger numbers are for the smaller grains. The hardenability is therefore increased with the coarser grains.

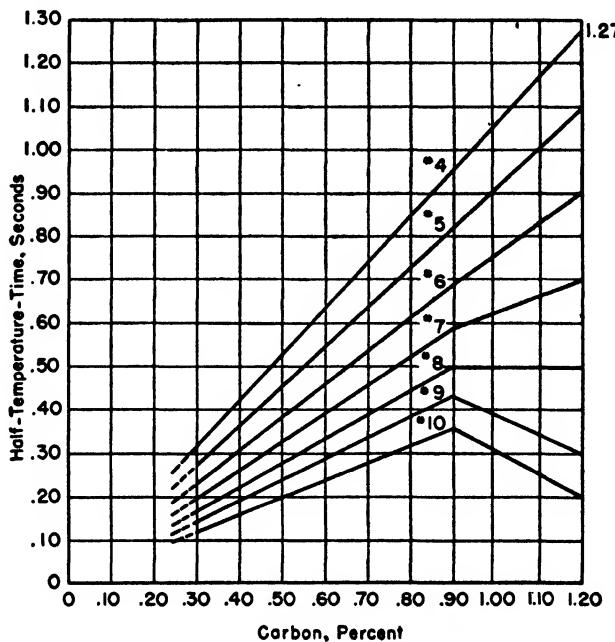


FIG. 6.25. Minimum half temperature quenching time for plain carbon steels to develop "critical" hardness of 50% martensite.

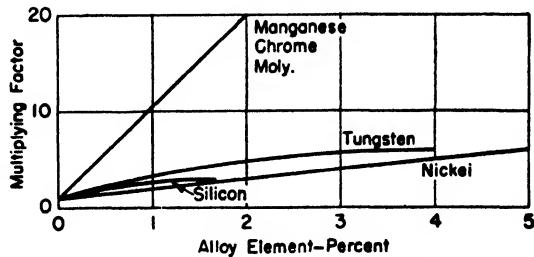


FIG. 6.26. Effect of alloys on the hardenability of steel.

The curves in Fig. 6.26 show the effect of some of the other alloys on hardenability. The effect is expressed as a multiplying factor. Its use will be illustrated by the following example.

<sup>1</sup> According to this system, the number of grains per square inch in a photomicrograph at  $\times 100$  is equal to  $2^{N-1}$ , in which the grain size index equals  $N$ .

**EXAMPLE.** It is desired to determine the half temperature time for a NE9440 steel of No. 7 grain size to develop "critical" hardness. This steel has a chemical composition of 0.4 C, 1.05 Mn, 0.5 Si, 0.3 Cr, 0.3 Ni, and 0.12 Mo. The multiplying factors of Fig. 6.26 for the percentage of each element present when multiplied all together and by the half temperature time for a plain carbon steel of 0.40 carbon and No. 7 grain size will give the half temperature time of the alloy. From Fig. 6.25, at 0.40 C and No. 7 grain size, the time is 0.26 sec. The factors for the other elements from Fig. 6.26 are respectively 10.9, 2, 3.8, 1.3, and 2.15. The product is 60.5, that is, 60.5 sec is the half temperature time for this steel to develop critical hardness.

Referring to Fig. 6.24, the critical hardness of 0.40 C steel corresponds to a Vickers Brinell number of 385. This is about 40 Rockwell C. This hardness would be obtained according to the above calculation in a quench where the half temperature time is 60.5 sec, or at a distance along the Jominy bar of 0.61 in. (see Fig. 6.22). As a check on the accuracy of this method, refer to the Jominy hardness curve for the same steel, Fig. 6.23. The same hardness, 40 RC, corresponds to a Jominy distance of 0.68 in. instead of 0.61 as calculated for the composition. The hardness at the quenched end, 56 RC = 617 Brinell, compares almost exactly to the maximum hardness for 0.40 steel, Fig. 6.24.

Note that cobalt, sulphur, and phosphorus were not included in the curves of Fig. 6.26. Both sulphur and phosphorus have only a minor effect on hardenability, although phosphorus is used in steels which may be precipitation hardened by heating to subcritical temperatures. Although this hardening is not comparable to quench hardening, it does serve a certain limited purpose. Copper acts in a similar manner. Cobalt is the only known element which *decreases* hardenability.

The curves presented make it possible to estimate the hardenability of any steel from the chemical composition, and may be of use to the engineer for this purpose, particularly when the Jominy curve for the steel is not available.

**6.8. Grain Size.** To the heat treater, grain size in steel is probably second in importance only to hardenability. A coarse grain size improves the hardenability over that for fine grain size in steel. But coarse grain steels also have lower impact and tensile strength and greater susceptibility to grinding cracks. It is a common mistake to assume that because the service stresses may be light, almost any kind of steel having the required hardness can be tolerated. What is not commonly known is that in quenching the part for hardening, it is very likely to be subjected to much higher stresses than it will ever have to support in service, and if made of coarse grained, brittle material, it may crack

either during or after quenching, or during grinding. Figs. 6.27 and 6.28 show the relation of grain size in plain high carbon steel, tool steel, and high speed steel all above 500 Brinell to the tensile strength and the

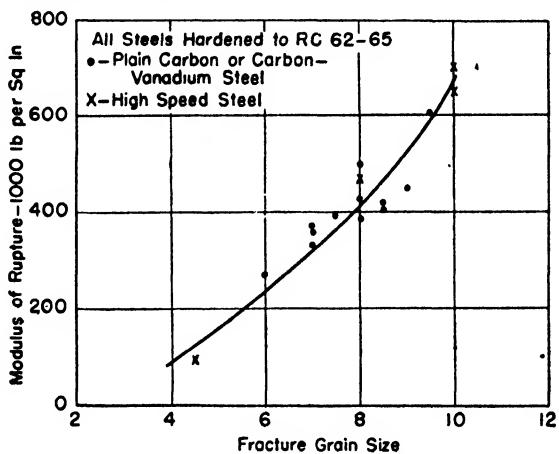


FIG. 6.27. Relation between grain size and the modulus of rupture in bending.

modulus of rupture in bending. The effect of large grain size in reducing impact strength is even more pronounced, as shown in Fig. 6.28.

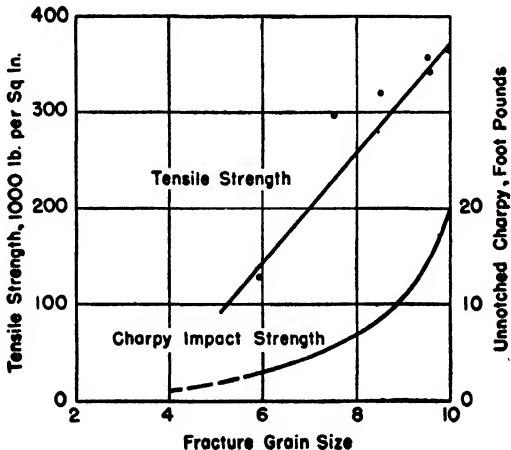


FIG. 6.28. Relation between grain size and both tensile strength and Charpy impact strength. (All metals tested at 60 Rockwell C.)

The mechanical properties of steels in the softer states (under 500 Brinell) are not affected to the same degree by coarse grain size, but the advantages gained through use of a fine grain usually are of great

enough significance that fine grain is specified for materials for structural applications. Fine grain results in higher impact strength, fatigue strength, and tensile strength, better resistance to fatigue crack propagation, and better machine finish. It is the best material for deep drawing and shows somewhat improved ductility as compared with a coarse grained steel of the same composition.

The control of grain size and the methods of measuring it are important problems for the metallurgist, and new advances are continually being made. Since these problems are highly specialized they will not be discussed here.

**6.9. Normalizing.** In steels containing 1 per cent or more carbon, previous processing treatments involving slow cooling from a high temperature frequently may cause the excess cementite to form a network around the grains. This network is very stable and it makes further heat treating operations more difficult because it is unaffected by ordinary annealing temperatures, and it does not go entirely into solution at the regular hardening temperatures. The treatment commonly employed to break up this network and to keep it from re-forming is known as *normalizing*. It consists of heating above the  $A_{cm}$  temperature line, Fig. 6.1, to dissolve the excess cementite in austenite, and then cooling at an intermediate rate, e.g., air cooling, so sufficient time is not allowed for the excess cementite to re-form a network or large plates. Instead, the structure is a mixture of fine cementite and pearlite, and is a little harder, stronger, and less ductile than annealed steel of the same composition.

Normalizing is also employed to *homogenize* structures in mild carbon steels, especially heavy forgings. Owing to unequal deformation in hot working, and possible thermal gradients during working, the structure of such parts may not be uniform. The normalizing treatment is performed at a high enough temperature (farther above  $A_{cs}$  temperature line than for full annealing) to permit the formation of a uniform austenite solid solution. The normalizing treatment is usually followed by heating to below the transformation temperature to promote softness and improve ductility. Steels given this treatment after normalizing generally have equal or slightly lower strength but greater ductility than before treatment; the two treatments are known collectively as *homogenization*.

**6.10. Surface Hardening.** There are many parts used in industry which must have a hard wear-resisting surface and a soft ductile core. Sometimes this soft core is desired to facilitate forming or machining operations, sometimes for impact resistance during service. For such a combination of properties, it is not feasible to harden and quench a

high carbon steel to obtain surface hardness, particularly when the hardness may be required on only a small area. Two other methods make possible such surface hardening. When the full surface is to be hardened, a method known as *case hardening* is usually employed. In it the surface is impregnated with carbon or some other hardening agent to give, through quenching, a hard surface. The hardenability of the core remains unchanged, and it retains its softness after quenching. Cyaniding, carburizing, and nitriding are operations of this type. The second method was developed especially for hardening small areas. A steel having the necessary hardenability is used and it is hardened locally, thus saving the cost of heating and the distortion which would result from hardening the whole piece; these might prove limiting factors if the part were large. Flame and induction hardening are employed for this purpose.

*Cyaniding.* The cyanide process is particularly applicable to small parts requiring a thin, hard, wear-resisting surface. Typical parts cyanided are small gears, ratchets, pawls, pins, bushings, screws, and small hand tools. The process consists in heating the steel in a molten bath of sodium cyanide and then quenching in water or oil. The time of heating will vary from several minutes to 4 hr, and a case-depth up to 0.025 in. is obtainable.

*Carburizing.* Carburizing is used for heavier parts or those which require a deeper case than is normally developed in cyaniding. Two general methods, pack carburizing and gas carburizing, are in use. In the former, the steel pieces, either stamped or fully machined and containing only a small allowance for finish grinding, are packed in solid "carburizing compound," and heated for periods ranging from 4 to 72 hr. The heating causes the formation of carbon monoxide gas which reacts with the iron to form carbon and CO<sub>2</sub>. The carbon dissolves in austenite and penetrates below the surface by diffusion. In the other method the pieces are heated in a furnace having an excess atmosphere of hydrocarbon gas and carbon monoxide. The same action takes place, but this method is faster and permits better control of the depth of the hardened area. The pieces removed from the carburizing pots have a surface carbon content ranging from 0.8 to 1.4 C. They are reheated to a temperature somewhat lower than that used in carburizing, then quenched in oil or brine to develop the required hardness. A preliminary higher-temperature quench may be used to refine the grain of the core if it has grown too much during the carburizing cycle.

Surfaces can also be decarburized if they are heated in a hydrogen atmosphere. Where this treatment is purposely employed, promotion of surface softness is usually not the direct purpose. Decarburization

is sometimes used to decrease carbon content of silicon steel sheet for motor applications.

*Nitriding.* Whereas almost any type of plain, low carbon steel or low carbon alloy steel may be carburized or cyanided, a steel containing a nitride-forming element (e.g., Cr, Al, Mo, V) is required for nitriding. The process consists in heating the parts in a sealed container through which is passed a stream of ammonia gas. The usual temperature is 1000 F, and the time cycle may range from 8 to 96 hr. The nitrided case may be up to 0.030 in. in depth, and is by far the hardest produced by any of the case-hardening processes. An advantage of nitriding is that distortion is reduced to a minimum. This is because of the low temperature used; and because the parts are cooled slowly no quenching is needed.

Besides the hardness and excellent wear resistance obtained, the surface has good resistance to corrosion by alkalies, crude oil, tap water, salt water (not in motion), ethyl gasoline, and other media, and retains its hardness at elevated temperatures. The process is relatively costly because a special steel must be used, the equipment is expensive, and a long time cycle is required.

When it is desired to case harden only part of the surface, those areas which are to be soft may be protected by a metal plating. Copper plating is the correct protection for the cyanide and carburizing processes, and tinning or nickel plating should be used to oppose nitriding.

Induction hardening and flame hardening will be discussed under the section on heat treating equipment. Use of these methods to produce surface hardness is increasing because of the short time in which the operation may be performed, the low costs, and the little distortion produced as compared with the furnace heating of pieces in the case-hardening methods. These advantages are especially important on large parts such as gears, or on parts processed on an assembly line.

*Case Depth.* In the literature, case depth is usually reported as the *total* observed by metallographic methods. This often leads the designer or shopman to believe that he can grind to almost the full case depth and still have uniform hardness or wear resistance. Such is emphatically not true. For example, cyanided parts should not be ground over 0.003 in. per side, no matter how deep the case is. On carburized parts the depth of "effective" or useful case will average about half the total. Nitrided parts should be finish-ground, polished, or lapped only deep enough to remove the "blush" or frosty deposit on the surface. This is true regardless of the time cycle or depth of case.

**6.11. Heat Treating Equipment.** *Heating.* The various types of furnaces used for heating operations are briefly described in the following paragraphs. Each may be heated by a coal, oil, or gas flame, or by electric resistors and, if properly constructed, a protective atmosphere may also be employed.

**BATCH TYPE.** Furnaces of this type may be classed broadly as horizontal or vertical, depending on the direction in which the work is introduced.

The horizontal batch furnace, known as the box furnace, is the oldest and still the most common type. It consists of a horizontal heating chamber of rectangular section, charged and discharged through a door or opening in front, the bottom being known as the "hearth." The low temperature oven (up to 1200 F) is provided with a circulating fan for speed and uniformity of heating. The medium (1200 to 1850 F) and high (over 1850 F) temperature furnaces may be provided with special gaseous atmospheres, suitable for brazing, sintering, and carburizing as well as for hardening and annealing. The larger furnaces may be furnished with car bottoms to facilitate charging.

The box furnace is characterized by simplicity of construction and operation, low first cost, good thermal efficiency, low maintenance cost, and adaptability to a wide range of work. Its chief disadvantages are poor utilization of working space and difficulty in handling long slim parts without their sagging or warping.

The vertical batch furnaces are usually cylindrical in shape and are of either the pit or the bell type. The *pit* furnace is placed partly or completely below the floor level, and opens at the top. It is particularly suitable for heating long parts such as tubes, shafts, and rods suspended from a top supporting fixture, or supported from the end and held in a vertical position. Loading in this manner gives minimum warpage. The pit furnace is also convenient for parts such as gears and sprockets which can be loaded in containers or on suitable fixtures for charging and discharging. The *bell* furnace consists of a cylindrical heating chamber, open at the bottom, which is lowered over a retort covering the work during both heating and cooling. Since the cooling operation is slower than the heating operation, one bell furnace can take care of several retorts. Furnaces of this type are especially suitable for annealing coils of strip or wire. For dense furnace loading, both types are provided with a motor-driven fan for circulating the furnace atmosphere, to provide more rapid and more uniform heating.

A variation of the vertical type furnace is the elevator type. It is a car furnace with an opening at the bottom. The charge is loaded on

the car platform, the car then rolled into position underneath the furnace and raised into the furnace by means of a motor-driven lifting mechanism. For certain plant layouts this type of furnace eliminates the need for transfer cars and switching tracks, and often saves floor space. It is suited for heavy work and for the precipitation hardening nonferrous alloys which must be quenched rapidly to retain a supersaturated solid solution. The quenching tank for such work is placed directly below the oven, thus facilitating a quick transfer.

**CONTINUOUS TYPE.** Furnaces of the continuous type are modifications of the horizontal batch type provided with a conveying mechanism to automatically carry the parts through the furnace. The fixed speed of the conveying mechanism, and the closely controlled temperature zones of the furnace make possible any time-temperature cycle of great repetitive accuracy on separate pieces. Variations in heating time, and in atmosphere and temperature, introduced by the hand operation of the batch furnaces are avoided, thus giving greater uniformity of product. The continuous type furnaces are very suitable for in-line production. Although standard sizes are available, "tailor made" furnaces are also made for specific jobs. The first cost of either is higher than for the batch type furnace, but the high thermal efficiency, improved performance, and the adaptability to a wide variety of parts of similar size make the continuous type of great importance industrially.

There are several different arrangements — belt, roller, and rotary types. In the belt type, the conveying mechanism is a wire mesh alloy belt or a thin sheet of silicon steel. The parts are placed directly on the belt for the trip through the furnace. The roller type employs a series of synchronously driven rolls to carry the parts. If the parts are long enough, they may be placed directly on the roll table. Shorter parts are placed on fabricated trays made of channels or rails, and for very small parts, these rails may be covered with wire or ribbon mesh. The roller type is therefore suitable for light, medium, or heavy work. In both the belt and the roller types, the work may be charged manually or automatically, and also discharged either way. In some production lines, or for shops where only one operator can be employed, it is desirable to have the charging and discharging doors adjacent to each other. This arrangement is provided by the rotary type continuous furnace. Besides the advantages mentioned, the rotary furnace is also popular for parts that must be handled individually to assure correct quenching.

**SALT BATH TYPE.** The molten salt bath, one of the oldest of the devices available for heat treating purposes, is used for (isothermal) quenching as well as for heating. Salts that are electrical conductors

may be heated by passing current through the bath between immersed electrodes. The electric current not only heats the bath but also sets up circulation of the salt which promotes uniformity of heating. Non-conducting salts are heated externally. Depending on choice of the salt, the bath may have a chemical action on the immersed part or the bath may serve as a protective atmosphere. The salt adhering to the surface prevents oxidation during the transfer of the part to the quenching tank, but the loss of salt makes the bath operation expensive. Heat losses are also considerable. Speed and uniformity of heating are promoted by the natural characteristics of the process, and salt baths are available for all temperature ranges used in current heat treating practice.

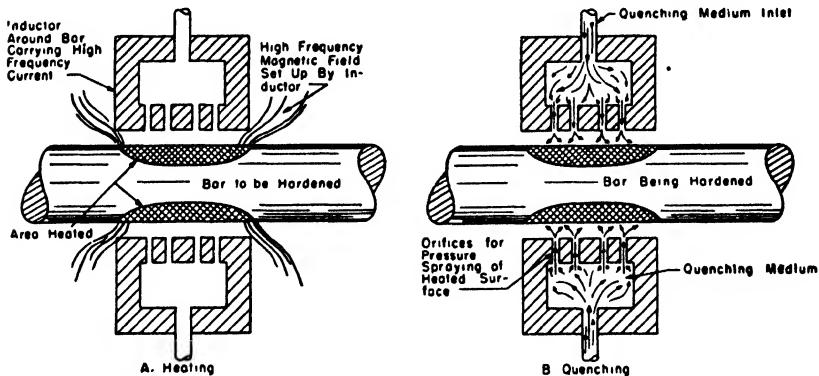


FIG. 6.29. Induction hardening part of the surface of a bar.

**INDUCTION HEATING APPARATUS.** A metal object to be heated may be located with respect to a coil carrying alternating current in such a manner that the electromagnetic field of the coil will set up strong heating effects in the desired areas. The coil may be of water-cooled copper tubing, it may have a special contour to suit the shape of the part being hardened, or it may be a single turn in the form of a hollow bronze casting as shown in Fig. 6.29.

The metal part placed in an induction furnace is heated by eddy currents within itself, and if the part is ferromagnetic, it will also be heated by its own hysteresis losses.

Frequencies range from normal 60 cycles to several megacycles. Up to 10,000 cycles, motor generator apparatus is most common. Above this, the source of power may incorporate vacuum tubes or spark gap circuits. Low frequencies are used for heavy parts which are to be heated through; high frequencies are for small parts or for those which are to be heated on the surface only.

This process supplied something long desired by the heat treater — a practical means of applying heat where desired and of keeping it away from areas where it is *not* wanted. Its value lies not only in the speed and efficiency, but also in the close degree of control which is possible. The nature of the induction process is such that it lends itself most readily to large scale, repetitive production. Even so, small lots and a wide variety of parts can be handled with good results.

One very promising application of induction hardening is for the teeth of large gears. Proper heating and cooling cycles make possible a hard wear-resisting surface having residual compressive stress. This stress opposes the tendency of the wiping action to open surface cracks and reduces pitting which would be caused by forcing lubricant in the tiny surface openings during service.

**FLAME HARDENING.** This method has also been used for hardening gear teeth and other intricate shapes. A steel having the necessary hardenability is chosen, as before, and the surfaces to be hardened are heated by a specially adapted gas welding torch, the torch flame being adjusted so the steel does not oxidize. The surface is heated so rapidly that it passes through the critical temperature,  $A_s$ , before the interior is affected. When needed, external quenching must be done immediately and it is usually followed by tempering to relieve the quenching stresses. For many parts, the quenching action of the adjacent cold metal is sufficient to produce the desired surface hardness.

**Surface Protection.** Solid, liquid, and gaseous media are all used to protect parts from surface oxidation during their heat treatment. Cast iron chips and carburizing compounds are two of the most common solid materials, and the protective action of liquid baths has already been mentioned. Gaseous media (controlled atmospheres) for heat treating are of comparatively recent development. The choice and control of gaseous media are very critical because some of the gases which prevent oxidation and scaling in steel generally cause carburization or decarburization also, which may prohibit their use.

**Cooling or Quenching.** Water, oil, and air are the universal quenching media. The relative cooling power of these three agents is about as follows:

<i>Cooling Power<sup>1</sup></i>	
	(H)
Water	2.50
Oil	0.50
Air	0.02

<sup>1</sup> Grossmann, Asimow, and Urban, "Hardenability of Alloy Steels," American Society for Metals, 1938, p. 124.

Because of the rapid rate of cooling, which may reach 6000 F per sec at times, the quenching operation is the most critical one encountered in heat treating. It is here that the equipment, and, more important, skill and experience in manipulation count the most.

Molten salt baths, very often the same ones used for heating, may be used, particularly for isothermal quenching operations. Slower rates of cooling, when required, may be had by the use of an insulating or retarding medium such as dry sand, lime, ashes, or mica dust. Still slower rates of cooling are obtained by holding the charge within the furnace, applying just enough heat, if necessary, to obtain the cycle desired.

*Auxiliary Equipment.* Every furnace should be provided with pyrometers to indicate, record, and control the furnace temperature. Gas processing equipment is also used when the furnace is to be furnished with a protective atmosphere.

Associated with the heat treating process is equipment for determining hardness, detecting cracks, and performing other tests; and, in many shops, equipment for cleaning, plating, welding, and forging.

Heat treating was formerly carried out in separate departments — often in some dark, hot, smoky, noisy, messy corner of a building — but today the trend is toward heat treating in line of production. Contrary to what one might suppose, this does not always mean expensive continuous equipment — the small batch-type furnace also has its place in such operations. Electric induction heating is contributing more and more toward this desirable end.

**6.12. Relation of Design to Heat Treatment.<sup>1</sup>** The fundamental principles of good design from a heat-treatment standpoint are quite simple. Steel has a certain strength depending upon its analysis, quality, and the heat treatment to which it has been subjected. When subjected to a combination of forces beyond its ultimate strength, the steel cracks or fails, owing to the combined action of (*a*) the internal stresses set up during fabrication and heat treatment of the parts, and (*b*) the external forces of service.

Sometimes the internal stresses alone exceed the strength of the metal and the parts crack in hardening. Again, the internal stresses may tax a high percentage of the total strength, and failure will develop in service under relatively light loads. The useful strength of a part therefore decreases in proportion as the internal stresses increase.

These internal stresses arise from many causes, but the most serious by far are those developed in quenching as a result of differential cooling.

<sup>1</sup> Much of this section is from the Metals Handbook by permission of the author, F. R. Palmer, and the publisher, the American Society for Metals.

This differential cooling (or more accurately, temperature gradient<sup>1</sup>) is largely a function of the size and shape of the piece being quenched, that is, the design. *The basic principle of successful design is thus to plan shapes which will keep the temperature gradient throughout a piece at a minimum during quenching.*

The manner in which temperature gradients give rise to internal stresses in steel<sup>2</sup> may be explained from dilatometer curves, such as shown in Fig. 6.16. The curve corresponding to full hardening registers a permanent increase in volume, while the air cooling (partial hardening) curve registers a decrease. Both conditions are obtained simultaneously when the gradient is sufficiently large, and the hardened outer shell tries to increase in volume but is held by the core which is trying to decrease. The result is enormous internal stress because a strain of 0.001 in. per in. in steel at room temperature sets up a stress of 30,000 lb per sq in.

The reason the pieces do not break is because the hard, brittle shell is under compression. If, however, the line of demarcation between the hardened and unhardened zones crosses an external surface, edge, or corner, then the danger of breakage is very great—a principle which is of immense practical importance.

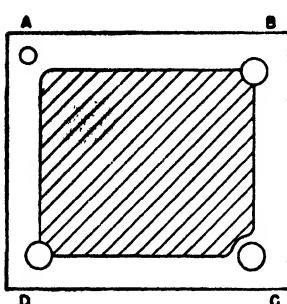


FIG. 6.30.

Consider a part, having four holes near the corners (Fig. 6.30), which is to be hardened. It is often recommended that, before hardening, holes near corners should be packed with some insulating compound such as asbestos rope. If holes A, B, and D have been so packed and C has been left

open, the unhardened core will be about as shown by the shaded area. Experiments show that holes B and D are more likely to crack than A and C, presumably because A and C are contained wholly within the hardened shell, whereas holes B and D are intersected by the plane of stress which separates shell from core.

Stresses set up by temperature gradients can do damage also at points

<sup>1</sup> A temperature gradient is the rate of variation in the temperature over a given unit distance. If, during quenching, the temperature of point A in the cube, Fig. 6.32, is 700 F, point B is 300 F, and the distance between them is 1 in., the temperature gradient between these points is 400 F per in. at that instant.

<sup>2</sup> Stresses are also set up in nonferrous metals by temperature gradients, but they are not quite so severe in most of these alloys because there is no transformation to a new lattice type.

remote from the junction of hardened and soft zones. Fig. 6.31a shows a section of a lamination die made of 1.10 carbon tool steel and completely hardened. After hardening, the lower right-hand corner was annealed, and (following the air-cooling dilatometer curve) it tended to shrink; whereas the rest of the metal was in the state shown by the water-quench curve. This caused a volume differential approaching

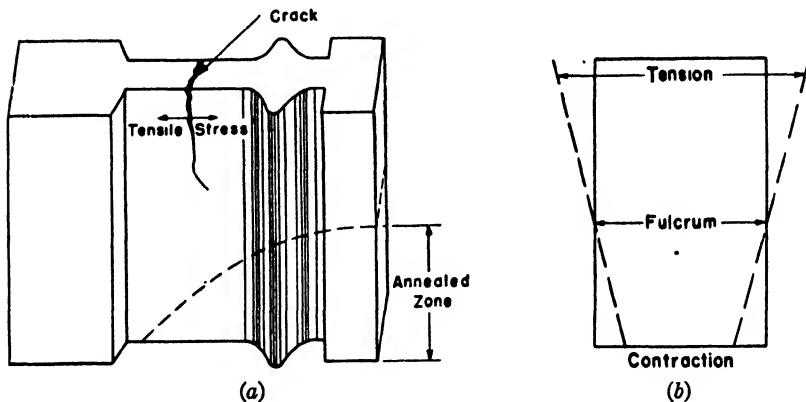


FIG. 6.31.

0.35 per cent, and the annealed zone, in attempting to contract, exerted a tensile force on the top surface (see Fig. 6.31b). The top surface always cracked in the same manner: sometimes right after annealing, sometimes during grinding or assembly, sometimes during service in the presses, and sometimes only after regrinding the dies (grinding removes the surface material which is under compression, thus upsetting equilibrium). When the annealing operation was eliminated the trouble disappeared.

Some shapes are almost impossible to harden because of the abruptness in the change of sections, but a certain latitude in the design is obtained when using an oil-hardening or air-hardening steel instead of water-hardening. All things being equal, the gradient between two points, e.g., A and B in Fig. 6.32, will be less in oil than in water and will be much less in air than in oil. Thus, a certain design may be perfectly safe for one type of metal and one type of coolant but unsafe for another.

Some hints and ideas for designing parts so they obey the fundamental principle of heating and cooling as uniformly as possible are illustrated in the following examples.

When a piece of metal is removed from the hardening furnace preparatory to quenching, it is presumably at a uniform temperature. As

soon as quenching begins, the temperature is different in almost every part of the section. This difference in temperature is due to two conditions. In the first place, the heat capacity or heat storage may be greater in one part of the section than in another, simply because there is more metal in one part than in another. This is illustrated by a tapered pin, as shown in Fig. 6.33. Obviously, the point of this pin will cool faster than the heavy section because there is less heat to be dissipated per square inch of cooling surface.

The rate of cooling is also affected by the shape of the surface. Fig. 6.34 illustrates a piece which is quite uniform in cross-section, but which will not cool uniformly. The protruding corners, such as *A*, are cooled from three sides so that the extreme corner is giving off heat from approximately seven times as great an area as it is receiving heat from.

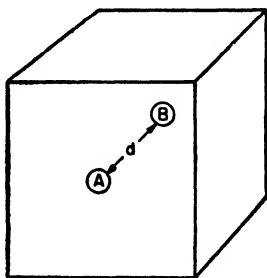


FIG. 6.32.

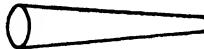


FIG. 6.33.

An edge, such as *B*, is cooled from two sides and is giving off heat to three times as great an area as it is receiving heat from. A point on a flat surface, such as *C*, receives heat from one side and delivers it to the other. The cooling area and the heating area are approximately equal. At a re-entrant angle, such as *D*, heat is being supplied to the surface through three times as great an area as it is being dispelled from, and this point will naturally cool last. It is impossible to get uniform cooling during the quench in the immediate neighborhood of such a sharp angle because the corner is inaccessible to the coolant, and vapor pockets may form. Differential cooling thus sets up heavy internal stresses at a point which is almost certain to receive stress concentrations in service, a very undesirable combination.

In a section such as shown in Fig. 6.35, there is a combination of the conditions given in Figs. 6.33 and 6.34. The heat capacity of the body, *B*, is much greater than that of the projection, *A*, and there is a sharp re-entrant angle at point *C*. It would be practically impossible to harden such a shape in water without cracking the sharp corner. Even

oil quenching would be doubtful on a piece of these proportions, and only by cooling in air could the thermal gradient be kept to a safe value.

The cross-section of the tool in Fig. 6.36a is made up of heavy and light sections, joined together with sharp re-entrant angles. A tool of this shape would be extremely hazardous to harden in either a water-

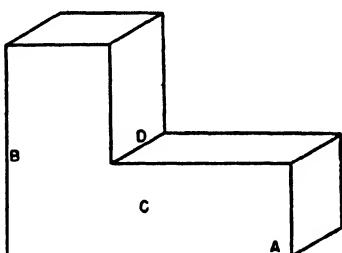


FIG. 6.34.

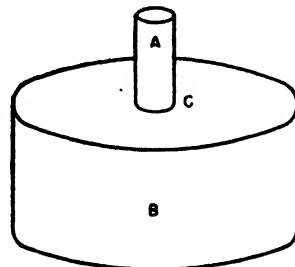
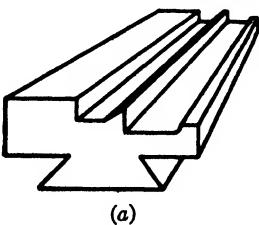
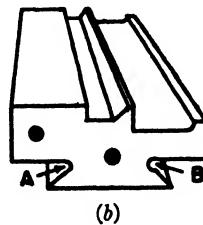


FIG. 6.35.

hardening tool steel or a high-speed steel. A corrected design is illustrated in Fig. 6.36b. Holes have been drilled through the two heaviest sections, and thus the weight of the metal has been fairly well balanced



(a)



(b)

FIG. 6.36.

throughout the cross-section of the tool. The sharp angles on the cutting edge cannot be eliminated because they are a part of the form of the tool. Two suggested treatments are shown for the angle at the base of the dovetail. The best treatment is shown at A, where a generous fillet is provided. An alternative is shown at B, where the corner has been undercut to provide a radius and still give the effect of a sharp corner on the dovetail. From the standpoint of quenching strain, the undercut form has little to recommend it, but it does have the advantage that there is no absolutely sharp corner in which stresses can concentrate.

Fig. 6.37 illustrates improper design in a double-ended side mill or spot facer. Each side of this tool has three teeth, with the teeth placed opposite each other. This is a badly balanced condition in the cross-

section of the piece and is made more serious by the sharp corner at the base of the teeth. Such a tool is almost certain to break at the junction between the light and heavy sections. This condition may be corrected by staggering the teeth on opposite sides of the tool and introducing a generous fillet at the base of each tooth.

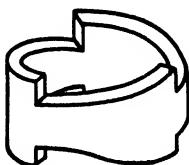


FIG. 6.37.

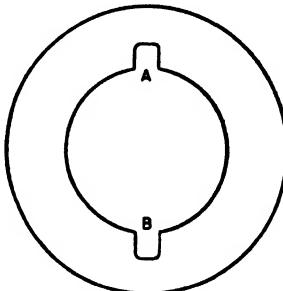


FIG. 6.38.

Fig. 6.38 illustrates two principles of design. This is a ring-shaped section containing two keyways on opposite diameters. The keyway *A* is shown with absolutely sharp corners. This is never good design. While millions of keyways are being made and used with sharp corners,

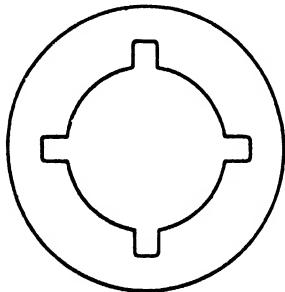


FIG. 6.39.



FIG. 6.40.

it does not alter the fact that it is a poor design and every effort should be bent toward making standard a round-cornered keyway, such as is shown at *B*.

The second interesting point about this ring is that, when it is quenched, it will not stay round. The section of the ring is weakened by the two keyways and almost invariably the ring will become oval. This condition may be corrected by cutting two more keyways at 90 degrees to the first two, as illustrated in Fig. 6.39. These keyways may serve no purpose but to balance the section and keep it round.

Fig. 6.40 shows, at *a*, the ideally sharp points on a steel cutting tool.

These points will be burned off in hardening. They should have a small flat surface as at *b*.

Success in preventing warpage and other forms of internal strain will be directly proportional to success in balancing the weight of the sections and producing uniform cooling conditions. Large dies of intricate design are sometimes made up in sections, which often simplifies the problem of heat treatment.

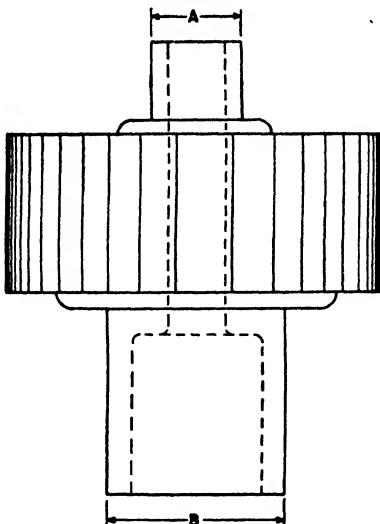


FIG. 6.41. Machine A and B 0.004" to 0.007" oversize.

Finish machine teeth and splines.

Case harden all over — 0.010" to 0.015" deep.

Hardness of case — 90 to 93 R15N.

Hardness of core — 45 to 50 RC.

Finish grind A and B. Material called for according to system in use.

**6.13. Heat Treatment Specifications.** With respect to heat treating, the engineer should specify what is wanted, not how to do the job. For instance, he should specify desired hardness and other requirements rather than heating temperatures and quenching media. Fig. 6.41 illustrates a satisfactory drawing specification for a case hardened gear wheel.

The function of the metallurgical engineer is to advise the designing engineer as to the best material and process, and to assist the planner, production man, and heat treater to obtain the results desired. It should be obvious that consultation between all the interested parties

*before* the design is completed is bound to give better results in the long run than trying to "doctor up" and salvage faulty jobs once production has started.

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"Metals Handbook," American Society for Metals, 1939.

### HEAT TREATMENT OF NONFERROUS ALLOYS

By DR. R. H. HARRINGTON

**6.14. Introduction.** Nonferrous alloys are those in which iron does not exert a predominating influence. In the majority of these alloys, iron is present only as an impurity or not at all. There are a few analyses, such as of certain aluminum bronzes, which show iron in relatively small percentages as an alloying element. The term "nonferrous" has often achieved a broader use to include such alloys as those of nickel, cobalt, manganese — alloys of metals which exist in several allotropic forms and, additionally, possess metallurgical properties similar to those of iron.

The chief "nonferrous" alloys finding engineering use are those of copper, aluminum, magnesium, zinc, and lead.

The heat treatments of nonferrous alloys are naturally divided into two classes: (*a*) those for cold-worked metals and cold-worked solid-solution alloys and (*b*) those for alloys possessing phase reactions that may be controlled by specific rates of heating and cooling.

The discussion of Class *a* will be limited to solid-solution alloys since, with the exception of pure copper, with its high electrical conductivity, *pure* metals find very limited structural use. The parts of the discussion applicable also to pure metals (especially after cold working) will be obvious by reference to Chapter I.

Relative to Class *b*, there are today 15 distinct types of solid-state phase reactions that may be controlled by heat treatment. Of these by far the most important is that of the precipitation of an intermetallic compound (or a solid solution) from the parent solid solution. The present discussion of this class will be limited to this type known as *precipitation hardening*.

**6.15. Fundamentals.** These will be only briefly mentioned here since they are fully discussed in Chapters I and II.

All metals and alloys are crystalline in the solid state, thus having their atoms arranged in regular geometrical configurations called

*lattices.* There are a number of types of these lattices, the chief being body-centered cubic, face-centered cubic, and hexagonal close-packed with each corner atom shared by all adjacent cells. At all times, however, it is necessary to remember that these lattice types merely specify a geometrical location of a space occupied by an atom, itself in motion within that space, or *sphere of influence*. Owing to imperfections there may be occasional vacant positions.

As the temperature of a metal or alloy rises, the motion of the individual atoms becomes more violent; interchange of positions, or a shifting of atoms through vacancies, and rates of the diffusion of atoms of one metal through the lattice of another increase markedly until finally the excited atoms break completely their lattice forces (bonds) and the metal or alloy starts to melt.

Different lattices define different phases. These phases are classified as metallic elements, solid solutions, or intermetallic compounds. Solid solutions, in turn, may be either of two types: *substitutional* or *interstitial*. Solid solutions generally have a rather wide range of chemical composition as do most liquid solutions. The lattices of some intermetallic compounds may have some solid solubility for excess atoms of the combining elements (and, sometimes, atoms of other elements). In a few isolated instances, an intermetallic compound lattice may have such wide solubility for excess atoms of either participating element that the distinctive properties (hardness and brittleness) of the compound are lost and merge into those for a solid solution.

Lastly, it must be emphasized that the derived equilibrium diagrams express composition-temperature relationships in the *absence of any strain* from cold working, from quenching, or from an externally applied force.

**6.16. Heat Treatment Definitions for Solid Solutions.** The alpha solid solution field of the copper-zinc equilibrium diagram, ranging from zero to about 40 per cent Zn in Cu, is shown in Fig. 6.42a and will serve to illustrate the heat treatment definitions for solid solutions.

It is necessary first to show briefly what takes place with slow cooling of a representative solid solution such as 85-15 brass (see Fig. 6.42a).

(1) The rate of cooling through the solidification zone,  $X' Y'$ , will determine the relationship of two effects inherent in each alloy: the rate of nucleation and the rate of grain growth of the nuclei. If the cooling is such that maximum rate of grain growth occurs for a low nuclei number, the solidified casting will be coarse grained.

(2) The rate of cooling through the solidification zone will also determine the amount of coring that will result for each grain between  $X$ , the Zn content for the first part of the grain to solidify, and  $Y$ , the

Zn content for the last part of the melt to solidify. Theoretically, with infinitely slow cooling, equilibrium would result in elimination of the coring and a solid solution free from strain. Fast cooling will accentuate composition gradients within the grain (coring) and will result in a thermally strained casting.

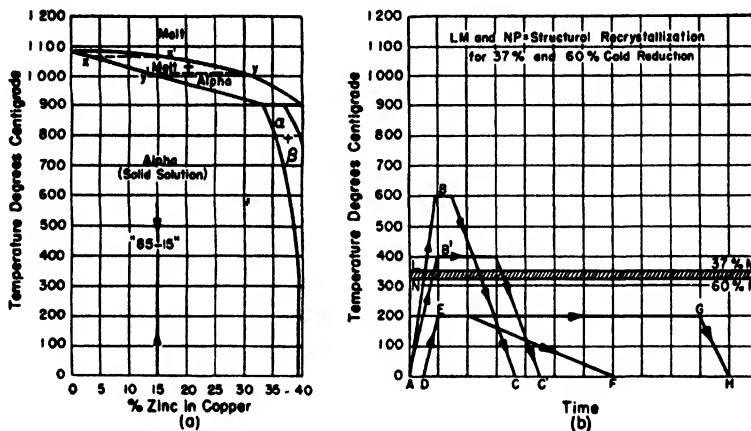


FIG. 6.42. Copper-zinc alloys.

- (a) Alpha solid solution range of Cu-Zn equilibrium diagram.
- (b) Heat treatments diagrammed for 85-15 brass.

(3) From  $Y'$  to room temperature, no phase change takes place within the alpha field and no markedly effective heat treatment is possible. However, two types of annealing may be useful: at relatively low temperatures for *stress relief*, and at suitably higher temperatures<sup>1</sup> to homogenize the structure (eliminate residual coring).

Therefore, the really effective heat treatments, so far as condition and properties are concerned, apply chiefly to cold worked solid solutions.

The lattices of solid solution alloys (and of metals) are elastic up to certain specific limits of elasticity. If the lattice be strained within its elastic limit and the cause of the strain be removed, the atomic locations in the distorted lattice tend, with time, to return to their equilibrium positions in the lattice of the original grain structure. This rate of *restoration diffusion* will vary with different materials and with different degrees of distortion. This lattice strain may be relieved by a commercial heat treatment (*strain or stress relief anneal*) consisting of heating the alloy, which has been strained (by cooling as a casting, by quenching, or by cold working) for a relatively short time at temperatures below

<sup>1</sup> In brass, annealing temperatures must be kept as low as practicably possible to prevent the loss of Zn by direct vaporization.

the recrystallization range; thus, for cold-worked material, maintaining the essential properties of the cold-worked solid solution. With most cold-worked materials, such a heat treatment reduces (or practically eliminates) distortion which would occur after machining. It also reduces, or eliminates, stress corrosion or season cracking, and grain boundary penetration of solder.

If the lattice distortion from cold working exceeds the elastic limit of the lattice, plastic deformation results along grain boundaries and successively preferred slip planes of the grain. A new degree of lattice bonding occurs, maintaining metallic continuity up to the limit of actual fracture. A higher degree of lattice distortion or strain occurs, and strain gradients of high degree are thus set up within the lattice. A certain, relatively minor, amount of the total strain is, of course, elastic, and with time this elastic strain tends to be relieved by restoration diffusion. The strain of the plastically distorted lattice is removed only by increasing the mobility of the atoms by an increase in temperature until they form a new set of strain-free lattice locations, whereupon new grains result and grow, and recrystallization occurs. The type of lattice, as for alpha brass, remains the same for the new grains. Time and temperature are both factors and the recrystallization temperature, maintaining time at temperature a constant, will vary with the composition, the degree of cold work, original grain size, etc. For 85-15 brass, maintaining annealing time constant at 4 hr, recrystallization to a minimum grain size occurs at 350 C for 37 per cent cold reduction and at about 320 C for 60 per cent cold reduction.

Recently it has been shown that in some alloys, such as 85-15 brass, under conditions of plastic strain (cold-worked lattice), it is possible to effect an induced age-hardening reaction at temperatures *below* those for recrystallization, producing new combinations of useful properties. It is thus possible, depending on the specific alloy and the amount it has been cold worked, to further increase its elastic properties by 20 to 30 per cent, coincident with increases of 10 to 20 per cent in fatigue strength, increases in hardness and electrical conductivity, and a marked increase in elongation. This is relatively new research<sup>1</sup> but, although much remains to be learned about these effects, such heat treatments are already finding engineering applications.

<sup>1</sup> "The Precipitation Reaction in Cold-Rolled Phosphor Bronze," R. H. Harrington and R. G. Thompson, *Trans. Am. Soc. Metals*, Dec. 1940, pp. 933-949.

"The Precipitation Reaction in Aged Cold-Rolled Brasses," R. H. Harrington and T. C. Jester, *Trans. Am. Soc. Metals*, March 1942, pp. 124-142.

"The Precipitation Reaction in Aged Cold-Rolled 1% Cd-Cu," R. H. Harrington and L. E. Cole, *Trans. Am. Soc. Metals*, 1943.

The heat treatments for solid solutions are diagrammed in Fig. 6.42b and are summarized as follows:

*Annealing.* The only true *annealing*, independent of cold working, is the heating of cast solid solutions to a temperature for homogenizing to eliminate dendritic segregation or coring, holding at temperature for the required time, and slow cooling to room temperature. (See curve *ABC* in Fig. 6.42b.)

*Recrystallization Anneal.* The elimination of the cold worked structure by heating above the recrystallization range for required time to produce new entirely unstrained grains, followed by slow cooling rates such as furnace cooling, cooling in air, or in a protective atmosphere is *recrystallization annealing*. Typical cycles are *ABC* or *AB'C'* in Fig. 6.42b.

*Stress Relief.* This is the elimination of elastic strain effected by heating for required times at temperatures below those of the recrystallization range, followed by slow cooling. See curve *DEF*, Fig. 6.42b.

*Induced Age-Hardening.* This treatment consists of relatively prolonged heating (4 to 100 hr) at specific temperatures, followed by furnace cooling, cooling in air or in a protective gas atmosphere. This heat treatment results in a marked increase in elastic properties, elongation, and endurance limit as well as stabilization of these properties for service at temperatures up to the temperature of the induced aging. A typical cycle is *DEGH* in Fig. 6.42b.

**6.17. Property Variations for Solid Solution Alloys. Effect of Grain Size and Shape.** Refinement in grain size tends to increase elastic properties, tensile strength, and hardness with a decrease in elongation. Extremely coarse grains, especially in the as-cast condition, tend toward actual brittleness and decrease in shock resistance. Coring tends to increase the brittleness of cast structures. The elongated, strained grains of cold-worked solid solutions lead to a variation of properties from with-rolling-direction to trans-rolling-direction. This variation is relatively minor and often disregarded for cubic lattices such as for copper and for aluminum alloys but it becomes very significant (as much as 30 per cent difference) for hexagonal lattices as for zinc and its alloys. Extreme cold rolling can effect *preferred* orientation with an extreme difference between with-rolling and trans-rolling properties in any case. Cold rolling (straining) decreases electrical conductivity.

*Effect of Solute Metal Concentration.* Increase of solute metal (alloying metal) content affects different properties in various degrees. Hardness, tensile strength, elastic properties increase slowly at first, then more rapidly, reaching a relative maximum usually before the solute metal boundary of the alpha phase field is reached. The tensile strength and hardness curves for annealed brass (Fig. 6.43) are good examples. In all important alloy systems, except for brass, the increase in solute metal content causes an initial rapid decrease in elongation, with successive increases of solute content having less effect. The elongation

curve for *annealed* brasses (Fig. 6.43) shows the orthodox decrease for increase in zinc content up to 5 to 10 per cent zinc and then, paradoxically, a marked *increase* with further increase of zinc content. This is still a metallurgical mystery but a very fortunate circumstance. Usually

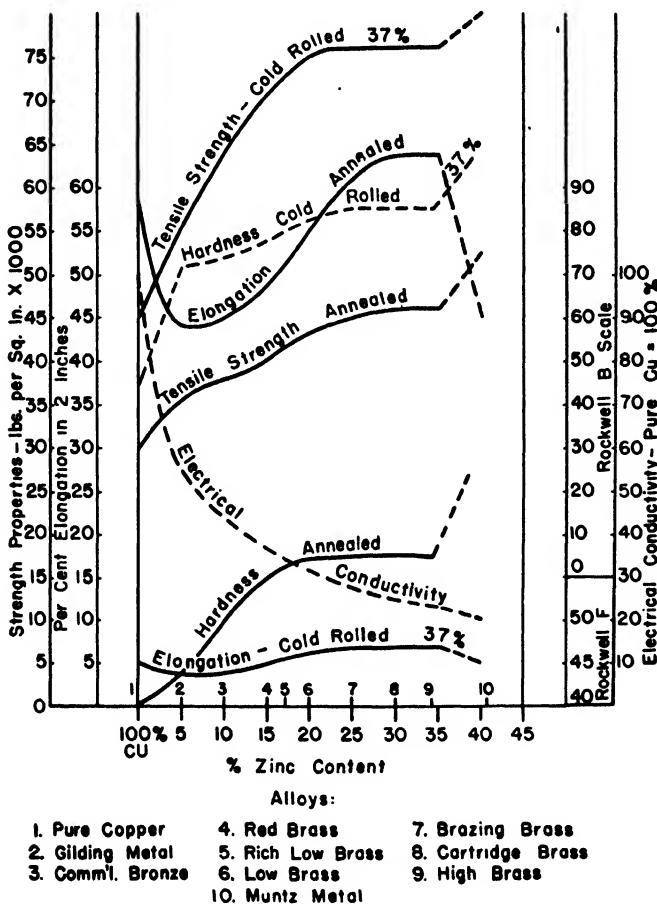


FIG. 6.43. Physical properties of rolled vs. annealed alpha brasses.

the increase in solute metal content renders solid solution alloys *less* workable while the converse is true for the brasses nearly up to the limit of practical alpha field solid solubility (about that of Muntz metal). The brass alloys do show the normal effect of increasing solute content on the electrical conductivity.

The effect of increasing solute content is to cause greater strengthening for the same amount of cold work, as shown by the comparison of the

two tensile strength curves for brass in Fig. 6.43. The effect on elastic properties is similar, but to a lesser degree. The anomalous elongation effect for brasses shows up to a minor degree for the cold rolled alloys, whereas the *normal* effect would be a progressive decrease with increasing solute content. The normal effect of solute content on hardness of

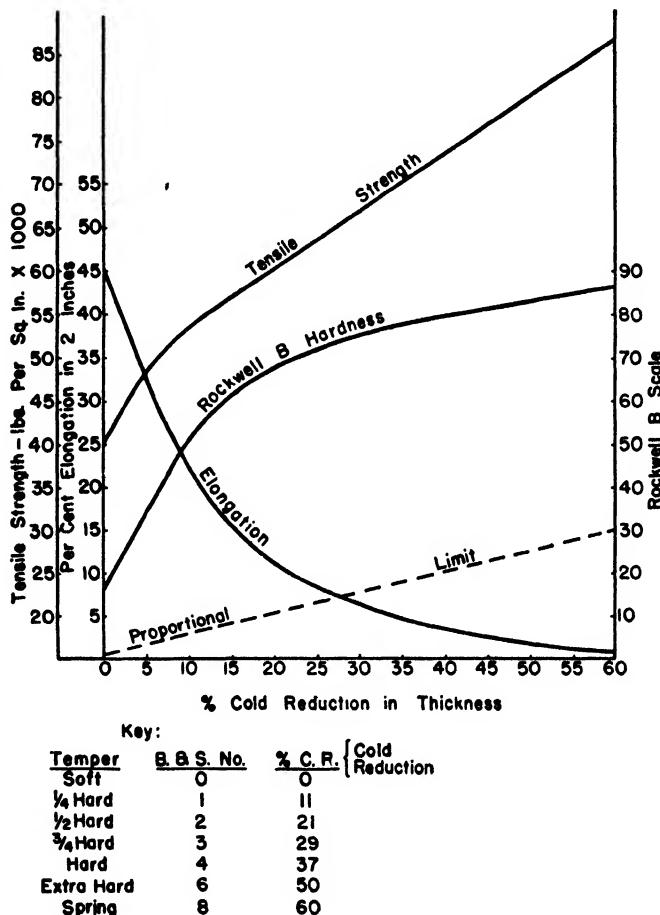


FIG. 6.44. Effect of cold work on 85-15 brass.

cold rolled alloys is to cause a progressive increase, more or less in parallel with the cold rolled tensile-strength curve. However, "hardness" is not a specific property and, for brasses, the cold rolled hardness curve strikes a compromise between the effects on tensile strength and on elongation.

*Effect of Increasing Amounts of Cold Work.* The effect of increased cold work on the properties for 85-15 brass is shown in Fig. 6.44. In this respect the alpha brasses react rather normally with respect to tensile strength, hardness, and elongation. However, for most solid solution alloys, the elastic properties (such as proportional limit) increase a bit more rapidly with increasing cold work. The effect of the strain of cold working is to lower the electrical conductivity, but only slightly: about 2 per cent drop for 85-15 brass, cold rolled 37 per cent, and  $2\frac{1}{2}$  per cent drop for 60 per cent cold reduction. The corresponding effects on the conductivity of 65-35 brass are decreases of  $2\frac{1}{2}$  and 3 per cent respectively.

Industry has standardized on certain *tempers* (degrees of cold work) and there are two systems of reference terms: tempers, and B and S numbers. The corresponding percentages of cold reduction are based on reduction of cross-section area for rod stock and reduction in thickness for strip. The comparison key for strip material is given in Fig. 6.44.

*Effect of Induced Aging.* Recent research<sup>1</sup> indicates that cold worked solid solution alloys are subject to heat treatment. This heat treatment consists in heating the strained material for required periods of time at temperatures below the recrystallization range. Such treatment results in coincident *increases* of elastic properties, hardness, elongation, endurance limit, and electrical conductivity. Although research results are not yet conclusive, it seems probable that either strain-domain precipitation or strain-domain formation of an ordered lattice is induced. Such heat treatment is already being applied in industry, one such case being steel shells.

The general effect on properties is diagramed in Fig. 6.45. For each property there are two aging curves with common origin for the un-aged cold-worked solid solution. The lower branch of each aging property shows the softening and, finally, the recrystallization curves for *pure* metals, which do *not* exhibit the induced aging effects. The upper branch of each property curve indicates the degree of possible increase in these properties due to aging. The degree of maximum aging effect depends upon the composition, the grain size, and the amount of cold work, and is a function of both time and temperature. The effect on tensile strength may be either a relatively slight increase or a similarly small decrease. The unique effect of this treatment is the coincident increase in *both* elastic properties and elongation, this effect not being produced by any other known treatment. This coincidence also appears

<sup>1</sup> Op. cit.

to be directly connected with the noted improvement in fatigue properties.

Table 6.1 gives detailed data concerning the strain-induced aging effect in cold worked solid solution alloys of 8 Sn phosphor bronze, 65-35 and 85-15 brasses, and 1 Cd-99 Cu.

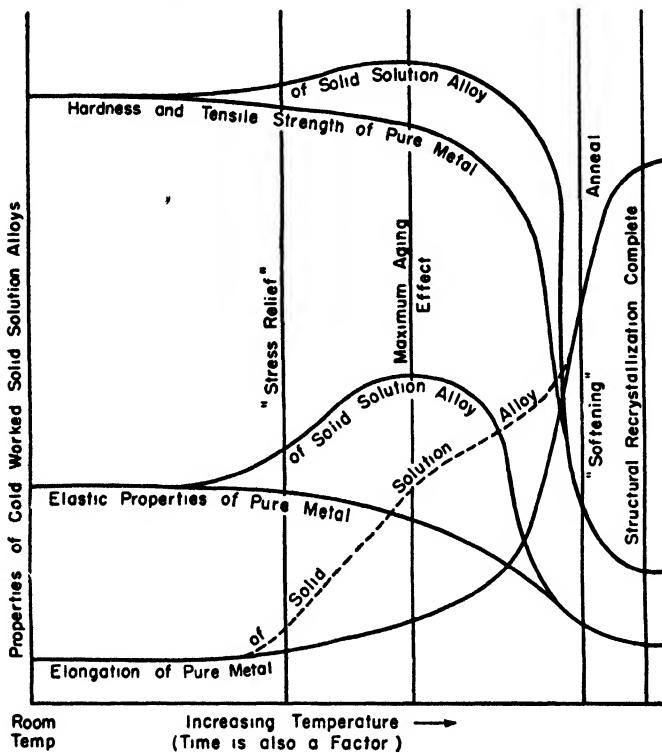


FIG. 6.45. Effect of "induced aging" upon heating cold worked solid solution alloys.

*Physical Properties of Representative Cold Worked Metals and Alloys.* These are given in Table 6.2, which shows proportional limits, elastic limits, 0.2 per cent yield strengths, tensile strengths, elongations, hardness, and fatigue strengths, depending upon available data.

**6.18. Heat Treatment Definitions for Precipitation-Hardening Alloys.** Much of the metallurgy for solid solution alloys applies also to this class and will not be repeated. In fact, precipitation-hardening alloys are simply constituted of one or more precipitation reactions originating within a solid solution lattice. The precipitating phase may be an essentially pure element, another solid solution, or an inter-

metallic compound. In the majority of these alloys, the precipitating phase is an intermetallic compound, the hardest of the solid metallic phases. It is to be expected that a dispersion of particles of a harder phase throughout a matrix of solid solution lattice will result in marked increases in such engineering properties as tensile strength, yield stresses, proportional limit, hardness, and endurance limit, with a decrease in elongation. Also, since precipitation from a solid solution requires a decrease in solute atom content, the matrix solid solution phase, after precipitation, contains less of the involved alloying elements and the electrical conductivity of the alloy increases, usually quite markedly.

TABLE 6.1. EFFECT OF INDUCED AGING ON SOLID SOLUTION ALLOYS

Material and condition	Prop. limit lb/sq in.	Elastic limit lb/sq in.	Tensile strength lb/sq in.	Elong- ation % in 2 in.	Rockwell B hardness	Elec. cond. %
8 Sn-P-Bronze (annealed)	16,700	20,000	56,700	62	..	12.4
90% cold rolled	55,000	60,000	136,500	1	107	12.0
Aged 100 hr 225 C	63,350	73,500	117,000	11	104	14.5
68% cold rolled	57,000	61,000	125,000	2	107	12.1
Aged 4 hr 250 C	58,000	71,000	109,000	16	102	12.9
50% cold rolled	47,200	51,600	108,000	8	102	12.2
Aged 10 hr 250 C	46,000	57,000	95,000	21	100	12.4
65-35 Brass (annealed)	10,000	..	40,000	40	10	26
60% cold rolled	28,000	30,000	93,500	2	88	24.6
Aged 10 hr 175 C	47,000	55,000	93,200	2	94	25.7
37% cold rolled	30,000	40,000	75,700	5	80	25.8
Aged 10 hr 175 C	37,000	47,500	76,000	7.5	85	26.4
85-15 Brass (annealed)	8,000	..	35,000	40	6	37
60% cold rolled	30,000	30,000	80,000	3	84	34
Aged 4 hr 200 C	40,000	55,000	81,500	4	87	35
37% cold rolled	26,300	45,000	69,000	6	76	34.6
Aged 4 hr 200 C	38,300	50,000	72,000	6	79	35.5
1 Cd-99 Cu						
60% cold rolled	28,000	30,000	64,000	5	73	91.3
Aged 10 hr 200 C	38,100	45,600	64,000	9	78	91.6
37% cold rolled	26,500	26,600	55,400	6	64	92
Aged 100 hr 150 C	33,750	35,300	55,800	10	73	93

As an example of this type of reaction, the precipitation-hardening portion of the copper-beryllium (Be) system is shown in the left-hand portion of Fig. 6.46a. The maximum solid solubility of Be in alpha

TABLE 6.2. SOME PROPERTIES OF ANNEALED AND COLD WORKED METALS AND ALLOYS

Material and condition	Prop. limit lb/sq in.	Elastic limit lb/sq in.	0.2% Yield strength lb/sq in.	Tensile strength lb/sq in.	Elong- ation % in 2 in.	Rock- well hard- ness	Fatigue strength 100 million cycles
8 Sn-P-Bronze (annealed)	16,700	20,000	..	56,700	62	25B	..
68% cold rolled	57,000	61,000	..	125,000	2	107B	22,000
65-35 Brass (annealed)	10,000	..	..	40,000	40	10B	12,000
60% cold rolled	28,000	30,000	..	93,500	2	88B	14,000
85-15 Brass (annealed)	8,000	..	..	35,000	40	6B	6,000
60% cold rolled	30,000	30,000	..	80,000	3	84B	15,000
1 Cd-99 Cu							
60% cold rolled	28,000	30,000	..	64,000	5	73B	..
3 Si-97 Cu (annealed)	12,000	..	..	60,000	40	55B	18,000
60% cold rolled	32,000	..	..	120,000	2	90B	24,000
100 Cu, OFHC (annealed)	5,000	..	..	30,000	25	30F	10,000
60% cold rolled	10,000	..	..	48,000	5	55B	12,000
2.5 Mg-0.25 Cr-Al (annealed)	..	..	14,000	29,000	25	..	17,000
60% cold rolled	..	..	36,000	41,000	7	..	20,500
1.2 Mn-98.8 Al (annealed)	..	..	6,000	16,000	30	..	7,000
60% cold rolled	..	..	25,000	29,000	4	..	10,000
100 Al (annealed)	..	..	5,000	13,000	35	..	5,000
60% cold rolled	..	..	21,000	24,000	5	..	8,500
7 Al-0.6 Zn-0.2 Mn-Mg (annealed)	..	..	26,000	42,000	10	..	..
Hard rolled	..	..	35,000	50,000	6	..	..
1.5 Mn-98.5 Mg (annealed)	..	..	17,000	32,000	16	..	..
Hard rolled	..	..	27,000	36,000	5	..	..
Alloyed zinc (annealed)	..	..	..	18-30,000	20-50	..	..
Cold rolled	..	..	..	26-50,000	20-60	..	..
99.9 Zn—special. Not work hardenable	..	..	..	16-19,000	40-70	..	..
1 Sb-99 Pb	..	..	..	2750-3000	30-40	..	800

solid solution in Cu is about 2.4 per cent at about 870°C, while the room temperature solubility is about 0.5 per cent. This means that, with slow cooling from about 850°C to room temperature, 1.9 per cent of Be is rejected from the alpha solid solution lattice in combination with Cu atoms in the form of new phases, each with its lattice distinctly different

from the others. Many binary systems are simple, involving only one precipitating phase. The Cu-Be system is a bit more complex, however, and it is necessary, for clear understanding, to describe what happens on slow (practical equilibrium) cooling of such a composition as that of 2 Be-98 Cu.

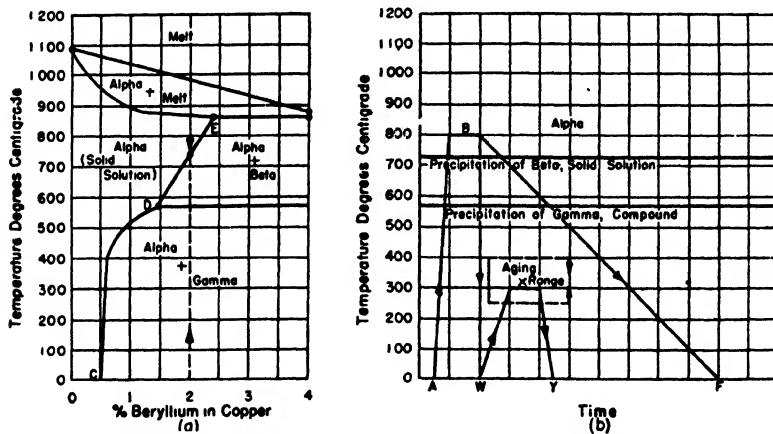


FIG. 6.46. Diagrammed heat treatments for precipitation reactions.  
 (a) Equilibrium diagram.  
 (b) Diagram of heat treatments for 2% Be alloy.

Cooling the molten alloy through its solidification range results in reactions similar to those previously described. In this case, the dendritic segregation (coring) may involve composition ranges in the extremes of 0.5 Be for the alpha solid solution to first solidify to about 4 Be in a second phase beta solid solution, the last part of the melt to solidify. Assuming that slow cooling or homogenizing annealing has eliminated the coring, then, at about 800 C, the alloy will be constituted of the normal alpha solid solution with atoms of Be randomly distributed within the Cu lattice.

Upon further slow cooling, nothing happens until the alpha boundary (*solvus*) is crossed at about 730 C. At this temperature, a second phase beta solid solution of about 5.5 Be begins to precipitate. As cooling continues to about 570 C, beta solid solution continues to precipitate. Reference to a diagram of more of this system<sup>1</sup> shows that the composition of the precipitating beta phase increases in Be content to about 6 per cent at 570 C.

At 570 C, the beta solid solution which has previously precipitated

<sup>1</sup> "Metals Handbook," American Society for Metals, 1939.

proceeds to break down at constant temperature (eutectoid inversion) into the familiar alpha phase (lower Be content), containing about 1.4 Be, and the gamma phase. This gamma phase is essentially the intermetallic compound, CuBe. Upon further cooling from 570 C to room temperature, the gamma phase (CuBe) continues to precipitate until the composition of the parent alpha solid solution reaches about 0.5 Be.

If precipitation-hardening alloys are heated above the solvus to cause a complete solution and if they then are quenched with sufficient rapidity, it is possible to retain complete (supersaturated) solid solution at room temperature. All alloys so treated tend to precipitation-age at room temperature. Rates of diffusion at room temperature in the specific alloy will determine whether precipitation will actually take place in practical finite periods of time at room temperature (*natural aging*), or whether it is necessary to reheat the alloy to elevated temperatures below the solvus to effect precipitation (*artificial aging*). The melting point of the solvent metal is a rough indication as to whether precipitation will follow at room temperature or at elevated temperatures. For example, (a) most lead-base alloys will precipitation-age at room temperatures or at even lower temperatures, (b) zinc-base alloys will precipitation-age from room temperature up to about 200 C, (c) some aluminum-base alloys naturally age at room temperature over a period of weeks and months and even years, while a few require artificial aging at temperatures up to 200 C, (d) copper-base alloys mostly require aging in the range of 200 to 600 C to effect precipitation, (e) most iron base alloys must be aged in the range of 400 to 900 C.

Thus the precipitation reaction in most of these alloys can be controlled to effect, in each case, the most useful engineering properties. Following the retention of the supersaturated solid solution by quenching to room temperature, precipitation-aging takes the natural course of continuity through the following stages: (a) aggregation of solute atoms within the solvent lattice up to the composition of the precipitating phase when (b) true nuclei of the precipitating phase separate from the solvent lattice and (c) grain growth of the precipitating phase takes place from these nuclei. Following nucleation of the precipitating phase there is a strengthening effect due to resistance of the particles to plastic deformation. With each alloy there is a critical grain size, inherently involving also the number of particles, of the precipitating phase to produce the maximum strengthening effect. This critical grain size may be submicroscopic in some alloys and optically visible in others.

Definitions involved by the heat treatment of this class of alloys are as follows:

**AGING:** Merely the alteration of structure and properties with the passing of time at ordinary temperatures. (Not specifically limited to precipitation.)

**AGE-HARDENING:** Literally, the increase of hardness in an alloy at ordinary temperatures; by common usage, however, synonymous with *precipitation-hardening*.

**AGING RANGE:** That temperature range within which the variation of length of time of aging will yield practically maximum precipitation-hardening or characteristically useful properties in the alloy; the higher the temperature; the shorter the time at temperature, owing to the higher rates of diffusion at higher temperatures. (Area for practical treatment of 2 Be-98 Cu about as indicated in Fig. 6.46b.)

**ARTIFICIAL AGING:** Specifically, the treatment at elevated temperatures to induce precipitation from a supersaturated solid solution in the alloy. (Indicated by curve *WXY* in Fig. 6.46b.)

**ANNEALING:** Consists in heating the alloy at suitable temperatures above its solvus for sufficient time to attain practically complete solid solution, followed by very slow cooling, as with furnace cooling. (Shown by curve *ABF* in Fig. 6.46b.)

**CRITICAL AGING (ALSO FULLY AGING):** The development of maximum precipitation-hardening properties in the alloy by producing critical dispersion of the precipitating phase by means of a critical heat treatment consisting of a specific solution quench followed by a specific aging treatment. (Cycle *ABWXY* in Fig. 6.46b.)

**CRITICAL DISPERSION:** For any precipitation-hardening alloy, the general distribution of critically sized particles of the precipitating phase throughout each grain of the parent solid solution so as to develop maximum, or critical, precipitation-hardening.

**INTERMETALLIC COMPOUND:** A phase, possessing its own typical lattice consisting of atoms of two or more elements, of which at least one is a metal, occupying specific geometrical positions relative to one another in an ordered orientation and in relative quantities expressed by simple whole number ratios of their atomic weights (such as CuBe, CoBe, NiBe, Mg<sub>2</sub>Si, A<sub>x</sub>B<sub>y</sub>, A<sub>x</sub>B<sub>y</sub>C<sub>z</sub>). Many of the intermetallic compounds have appreciable solubilities for excess atoms of their constituent elements.

**OVER-AGING:** Aging for a longer time than for critical dispersion, or at a higher temperature, or a combination of both, so as to cause grain growth and particle agglomeration of the precipitating phase beyond the stages of critical dispersion and thereby causing a decrease in hardness from the maximum. (Such treatments may be of benefit in sacrificing maximum tensile properties in order to apply some final shaping operation or to develop a particular property such as electrical conductivity in the CuBe alloys.)

**NATURAL AGING:** Precipitation from a supersaturated solid solution with the passing of time at room (or normal) temperature.

**PRECIPITATION-HARDENING:** The controlled development of a precipitation reaction in an alloy by heat treatment thereby to improve its properties, including hardness, for engineering usage. (Generally implies the complete cycle, such as *ABWXY* in Fig. 6.46b.)

**SOLUTION QUENCH:** The treatment to produce a supersaturated solid solution previous to critical precipitation-aging, consisting in heating the alloy to a suitable temperature above the solvus, holding at temperature for sufficient time to attain practically complete solution, finally quenching the alloy in some suitable medium so as to retain the solid solution at room temperature. (In the harder and stronger alloys, the solution quench is generally applied previous to machining, forging, drawing, or shaping and the essentially finished part is finally artificially aged. The solution quench is indicated by the curve *ABW* in Fig. 6.46b.)

**SOLID SOLUTION:** A metallic phase consisting of a typical lattice of mixed atoms of two or more elements in random orientation within this lattice.

**SOLVUS:** The boundary line between the field of the parent solid solution and the field containing the precipitating phase in the equilibrium diagram of the alloy system. (Illustrated by the curve *CDE* in Fig. 6.46a.)

**6.19. Property Variations by Precipitation Reactions.** The only difference between precipitation-hardening of cast alloy and alloy *previously worked* is that the previously hot or cold worked alloy is more dense than the same material cast. The difference in properties is slight except for elongation, which is usually markedly improved by previous working.

There are three types of application of precipitation-hardening: plain precipitation-hardening, cold working between the solution quench and the precipitation reheat, and cold working after complete precipitation-hardening. The effect of strain (cold working) in combination with precipitation treatments is complex<sup>1</sup> and will be only briefly indicated here.

**Plain Precipitation-Hardening.** The solution quenched alloy is in its softest condition; its tensile strength and hardness and electrical conductivity are at their minimum values while elongation is at its maximum. Quenching the alloy introduces strain gradients that are dependent upon the design of the casting or forging, and for some alloys this requires the use of fillets at sharp changes of contour or cross-section to avoid destructive warping effects. Many solution quenched alloys have sufficient ductility after quenching to allow for straightening should that be necessary.

The first effect of reheating for precipitation is to relieve the strains of quenching. Then, with longer time or higher temperature, as precipitation starts through the prenucleation stage, tensile strength, hardness, and electrical conductivity begin to increase while elongation drops off. As the reaction progresses through the nucleation stage to the critical dispersion stage, hardness, tensile strength, and electrical conductivity increase to a "maximum combination" of properties, with elongation at a minimum.

With over-aging and the coalescence and grain growth of the precipitated phase, tensile strength and hardness decrease rather abruptly while electrical conductivity and elongation tend to increase somewhat with the grain growth.

These variations in properties are diagramed in Fig. 6.47. Even those alloys (several aluminum base compositions) that *naturally age*

<sup>1</sup> "The Role of Strain in Precipitation Reactions in Alloys," R. H. Harrington in "Age Hardening of Metals" (symposium), American Society for Metals, 1939.

over a period of weeks to practically full strength must nevertheless be artificially aged to insure consistent results, relieve the quenching strains, prevent shipments of incompletely aged articles, and to eliminate the cost of storage while naturally aging.

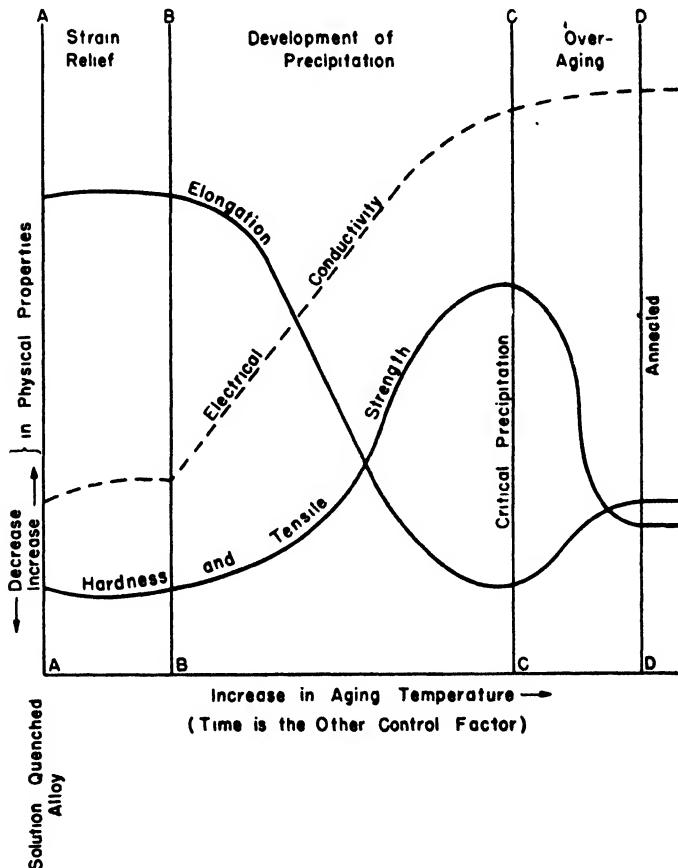


FIG. 6.47. General effect of precipitation on physical properties.

**Effect of Cold Work Intermediate to Quenching and Aging.** The effect of cold working after the solution quench and previous to reheating for precipitation is twofold: maximum precipitation-hardening properties are increased, and the temperature and time for precipitation are decreased somewhat. These effects, of course, depend upon the amount of strain from cold work, and this in turn varies with alloy composition. Too much cold work will result in internal ruptures and checks, with resultant lowering of elastic properties, elongation, shock resistance,

etc., even though the tensile strength and hardness may be increased. In general, copper base alloys of this class should not be cold reduced more than 50 per cent without intermediate solution treatments. Aluminum base alloys may be cold reduced more than 50 per cent but many aluminum alloys thus treated are sensitive to another effect:

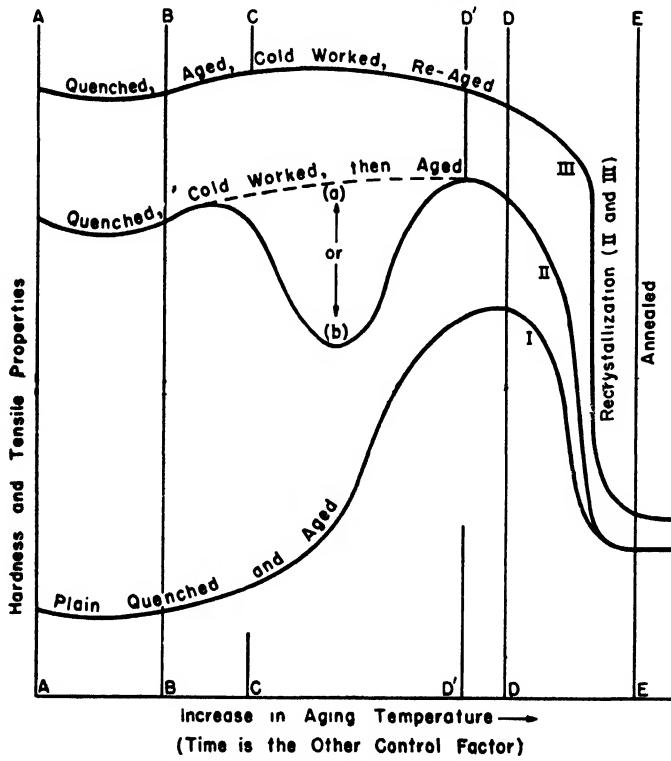


FIG. 6.48. Effect of cold work combined with precipitation.

concentrated precipitation in grain boundaries and along distorted slip planes, which results in marked embrittlement and lowered corrosion resistance. Chiefly for these reasons copper base alloys of this class, which have sufficient elongation as solution quenched, are cold rolled to increase the final tensile properties, whereas the aluminum base alloys that are structurally sensitive to embrittlement are solution quenched and aged *after* cold forging or shaping. Such practical complexities are studied in detail, and practical production methods are established for each important alloy.

Curve II of Fig. 6.48 shows the effect of precipitation-hardening of a cold worked supersaturated solid solution. The curves show the

effect of aging on hardness and tensile properties. Curve I is for plain precipitation-hardening, as shown in Fig. 6.48.

Following the aging of Curve II, the first effect is strain relief from *A* to *B*. From *B* to *D'*, the cold worked supersaturated solution takes one of two paths. Either effective precipitation occurs before any recrystallization, as in curve *a*, and the precipitated particles block the recrystallization, thus maintaining and perhaps increasing the cold worked solution properties; or some recrystallization or annealing effect takes place, as in curve *b*, before precipitation becomes effective to stabilize the remaining cold work properties and even to cause a further increase to maximum properties at *D'*. It will be noted that the effect of intermediate cold work is to decrease the maximum age-hardening temperature (or time) from *D* to *D'*. It also seems probable that intermediate cold working causes a slight increase in precipitation over plain precipitation-hardening.

*Effect of Cold Work after Complete Precipitation-Hardening.* A few alloys are still too low in strength after complete (plain) precipitation-hardening to be of much interest but still retain enough ductility for subsequent cold working. Maximum combination properties are achieved by cold working *after* complete precipitation-hardening whenever this is feasible. Such treatments are readily applied to standard rod, wire, sheet, and strip stocks.

The effect of re-aging (*double aging*) alloy material that has been previously precipitation-hardened and then cold worked is shown by Curve III in Fig. 6.48. The first effect is that of strain relief. The next effect is to cause further precipitation (at *C*), induced by cold working the solid solution matrix of the previously precipitation-aged material. From *C* to *D'* the properties remain relatively unaffected. Actual structural recrystallization, coincident with over-aging, takes place between *D* and *E* as coalescence and grain growth of the precipitated phase (along with re-solution at temperature *D*) eliminate the blocking effect of the precipitated phase. By this third treatment, the cold worked effect and properties are maintained (stable) until the service temperature actually exceeds that for maximum age-hardening (at *D*).

This treatment is a relatively new development and is finding its way into industry today for several special alloys, one of which is Cu-0.4 Cr-0.1 Be.

**6.20. Properties of Some Representative Precipitation-Hardenning Alloys.** There are 200 or more precipitation-hardening alloys in industry today. Table 6.3 cites the properties for three copper, two wrought aluminum, two cast aluminum, and one cast magnesium alloy. There

are also quite a number of iron and nickel base alloys in this class, particularly for spring and high temperature service. There are one or two zinc alloys of this type; but they are used in the wrought condition,

TABLE 6.3. PROPERTIES OF SOME PRECIPITATION-HARDENING ALLOYS

Alloy	Con-dition	Prop. limit lb/sq. in.	Elastic limit lb/sq. in.	0.2% Yield strength lb/sq. in.	Tensile strength lb/sq. in.	Elon-gation % in 2 in.	Rock-well hard-ness <sup>1</sup>	Electri-cal conduc-tivity Cu = 100%	Endur-ance limit <sup>2</sup> × 1000
2 Be-98 Cu	Q	8,000	..	..	70,000	45	70B	17	..
	P	46,000	55,000	..	175,000	6	38C	20	36
	W	55,000	80,000	..	193,000	2	40C	22	38
0.4 Be-2.6 Co- 97 Cu <sup>+</sup>	Q	..	..	..	45,000	30	30B	25	..
	P	45,000	55,000	..	110,000	10	20C	50	36
	W	55,000	65,000	..	125,000	7	30C	55	37
0.1 Be-0.4 Cr- 99.5 Cu <sup>+</sup>	Q	..	..	..	..	..	..	35	..
	P	20,000	25,000	..	50,000	15	60B	70	..
	W'	38,000	45,000	..	70,000	10	77B	75	..
4 Cu-0.5 Mn- 0.5 Mg-Al (balance)	Q	..	..	10,000	26,000	20	..	45	11
	P	..	..	40,000	62,000	20	..	30	15
4.5 Cu-0.8 Si- 0.8 Mn-Al (balance)	Q	..	..	..	..	..	..	35	..
	P	..	..	35,000	57,000	18	..	40	15
	Q	9,000	..	16,000	26,000	5	..	39	..
7 Si-0.3 Mg-Al (balance)	P	14,000	..	22,000	32,000	3	..	39	8
	P'	18,000	..	30,000	38,000	2 5	..	40	..
4 Cu-96 Al	Q	10,000	..	16,000	30,000	6	..	..	6
	P	15,000	..	22,000	35,000	4	..	..	6.5
9 Al-2 Zn- 0.2Mn-Mg	Q	..	..	14,000	39,000	10	..	..	11
	P	12,000	..	20,000	39,000	3	..	..	11

Q As quenched.

P Quenched and precipitation-hardened.

W Quenched, cold worked, then precipitation-aged.

W' Quenched, precipitation-hardened, then cold worked.

+ and P' General Electric patented alloys and heat treatment.

<sup>1</sup> The hardness for aluminum and magnesium alloys, which is usually by Brinell instead of Rockwell tests, is omitted to avoid confusion. In general, the aluminum and magnesium alloys have hardness values, heat treated, in the range of 30 to 60 Rockwell B.

<sup>2</sup> The endurance limit for the copper alloys is for 100 million reversals of stress while that for aluminum and for magnesium alloys is for 500 million cycles.

and internal friction heat from cold working serves to precipitation-harden them coincidentally with the working. These zinc alloys have recrystallization (softening) temperatures at about 100 to 115 C, whereas pure zinc and its solid solution alloys tend to recrystallize at room temperature. One complex lead alloy precipitation-hardenes slightly above and at room temperature while the rest of the lead alloys either age or recrystallize at or below room temperature.

**2 Be-98 Cu.** This alloy is characterized by its exceptionally high tensile strength and hardness and very good endurance limit. Addi-

tionally, it has a shock resistance of about 7 ft-lb and a maximum service temperature of about 250 C. (Cold rolled brasses and bronzes have service temperatures of 150 to 175 C.) It has exceptional wear resistance. Some of its uses include parts for the Garand rifle and the variable pitch Hamilton propeller, and many spring applications.

**0.4 Be-2.6 Co-97 Cu.** This alloy is nearly the equal of beryllium-copper in elastic properties and endurance for spring applications and, additionally, has a shock resistance of 35 ft-lb, twice its conductivity, and a maximum service temperature of 450 C. It is used for resistance welding electrodes, soldering-iron tips, pole shaders, structural high strength castings, electrically conducting bearings, bushings, and springs.

**0.1 Be-0.4 Cr-99.5 Cu.** This alloy sacrifices some of the strength properties of the preceding composition but has 50 per cent higher conductivity, shock resistance of 45 ft-lb, and a maximum service temperature, for the *W'* condition, of 500 C. Depending upon its specific properties, it is used for the same applications as the preceding alloy. (These are known as Trodalloys 1 and 7.) For rod, wire, sheet, and strip this alloy is finished by cold drawing or by cold rolling *after* complete heat treatment.

**4 Cu-0.5 Mn-0.5 Mg-balance Al; 4.5 Cu-0.8 Si-0.8 Mn-balance Al.** These two alloys are representative of about eight wrought aluminum alloys that are used for forgings, extrusions, sheet, and strip. Generally they are completely heat treated *after* cold working. The cold working is done with the materials in the solution-quenched condition. Natural aging would prevent this, so these alloys are in the artificially aged class.

**7 Si-0.3 Mg-balance Al (alloy 356); 4 Cu-96 Al (alloy 195).** These are the two chief sand-casting heat-treatable aluminum alloys. Heat treatment makes alloy 356 by far the stronger but alloy 195 has somewhat better shock resistance. There are other special compositions for permanent mold and die castings.

**9 Al-2 Zn-0.2 Mn-balance Mg.** This is one of the two chief sand-casting heat-treatable magnesium alloys. There are about nine commercial alloys of magnesium (wrought or cast), all containing from 3 to 10 per cent aluminum with various small additions of zinc, manganese, nickel, silver, etc.

**6.21. Heat Treatment Atmospheres and Equipment.** Heat-treating furnaces have been adequately described under the section on steel. The same batch and continuous conveyor types may be used for heat treatment of the nonferrous alloys. The continuous *strand annealing* type of furnace is also used for solution treating strip and wire which, later, is precipitation-aged in coils in batch type furnaces. Usually the

solution treatments (for precipitation hardening) are applied in separate furnaces, designed for more efficient operation at the higher temperatures, while annealing (of cold worked solid solution alloys) and precipitation-aging are done in furnaces designed for lower temperature operation.

Temperature control for heat treating of aluminum, magnesium, and zinc base alloys must be very accurate, within a range of  $\pm 5$  C. Such accuracy is not generally required for annealing treatments.

Heat treating in controlled atmospheres is required for many of the nonferrous alloys, especially for strip and wire. A good neutral or slightly reducing atmosphere is usually sufficient to prevent surface oxidation, scale, and discoloration. The wire or strip, in some instances, is finished with a light pickling dip. Some alloys may require a special atmosphere. For example, for solution treatment at 900 C, the Trod-alloys, in strip and wire form, require an atmosphere free from oxygen, carbon dioxide, and water vapor, although they may be aged at 480 to 500 C in any neutral atmosphere.

Molten salt baths, electrically heated, are the most efficient conductors of heat and give accurate easy temperature control. These find considerable use for annealing and aging, especially for strip and wire. However, special salt mixtures must be used for specific alloys in order to reduce surface chemical attack to a satisfactory minimum. Usually wire and strip under 3 mils in diameter or thickness should be heat treated in controlled atmospheres (in any case).

**6.22. Conclusion.** Nonferrous alloy compositions and applications are legion. Only brief descriptions of alloys and their properties affected by heat treatment have been given here. There are three salient points:

(1) Most alloy applications in the electrical industry depend upon elastic properties and/or endurance limit for structural performance.

(2) Frequently a number of alloys having similar tensile properties may be suitable for the same application, the final choice depending upon such other properties as temperature stability, electrical or heat conductivity, magnetic properties, corrosion resistance or oxidation resistance, wear resistance, resistance to impact, modulus of elasticity, and inherent fabrication properties for economic production. Not infrequently these "secondary" properties are of primary importance, so engineers are urged to consult the metallurgists on complex problems involving selection of material.

(3) When consulting a metallurgist, the engineer must be prepared to furnish a complete description of the desired part, including all details of the imposed operating conditions (such as service temperatures, corroding media, and method of attaching to other parts of an assembly).

## REVIEW QUESTIONS

1. Of what operations does hardening of steel usually consist? Annealing? Tempering? What is the purpose of each?
2. How does the dilatometer curve show the temperature of transformation for different rates of cooling?
3. What is meant by a split transformation?
4. How are the  $T-T-T$  curves developed? Explain the structural changes indicated by a cooling curve on the  $T-T-T$  diagram, e.g., curve *B* in Fig. 6.18.
5. Define hardenability. How is hardenability of carbon steel affected by carbon content and grain size? In general, how do alloys affect hardenability? Which ones seem to have the greater effect?
6. How may Jominy end-quench tests be used to select a steel which will give a specified hardness gradient for a given quench, say in oil or in water?
7. What properties are usually present in fine grained steel as compared with a coarse grained steel of the same composition?
8. What is normalizing? For what purpose is it employed in carbon steels having more than 1 per cent carbon? When used for medium carbon steels and followed by reheating to below the transformation temperature, what properties are obtained? What name is given collectively to these two treatments?
9. It is desired to case harden the following parts: (a) a small gear (very little distortion permitted, and no further machining); (b) a turbine valve (absolutely true shaft — no further machining or grinding); (c) a refrigerator crankshaft (remove 0.005 in. in finish grinding).  
Indicate the case hardening method which would be most suitable. Which would be the more expensive?
10. What principle of design should be followed to minimize cracking caused by internal stress resulting from heat treatment?
11. Describe how hardness, strength, elastic limit, and elongation change in a cold worked solid solution alloy with increasing temperature from room temperature to above the recrystallization temperature. Is stress relief obtained above or below the softening temperature? What is induced aging?
12. Describe the variations in properties of a precipitation-hardening alloy with reheating after the alloy has been solution quenched. How is solution quenching accomplished? What is the effect, in general, of combining cold working with precipitation, both before aging and after aging?

## REFERENCES

- "Metals Handbook," American Society for Metals, 1939.
- "The Metallurgy of Modern Alloys," in *Heat Treating and Forging*, current series. (Definitions of Heat Treatments in issues of Sept. 1942, Oct. 1942, Dec. 1942, and Equilibrium Diagrams in issues of March, April, May, and June, 1943.)

## CHAPTER VII

### CORROSION

By J. F. YOUNG

**7.1. Introduction.** Corrosion may be defined as the undesirable and destructive chemical reaction of a material and its environment. Corrosive action, usually associated only with metals, is considered separate from destruction by mechanical means, such as erosion, although corrosion and erosion often operate together, promoting each other, and in some types of service they may be difficult to distinguish. Of the common types of corrosion, those about which most is known can be explained on the basis of the electrochemical corrosion theory. Although it cannot be said that this theory will explain all types of corrosion, it does cover most of these reactions and will be used as the basis of the following discussion.

In the United States, each year corrosion causes millions of dollars' worth of damage to structural and decorative metal parts. Annual replacements of this type have been estimated to average as much as 2 per cent of the total tonnage of metal in use. An appreciation of corrosion phenomena and methods of limiting corrosion effects are therefore essential to engineering, both because of the tremendous economic waste involved and because of the possible risk to human life.

At the outset, it is emphasized that no metal in use today will resist the attack of all environments. There is no such thing as a "stainless," noncorroding metal — all will corrode under certain conditions.

#### PRINCIPLES OF CORROSION

**7.2. Conditions Necessary for Corrosion.** In the region surrounding a metal which is being corroded, three conditions must exist. (1) At least two points on the metal surface must act as electrodes for the flow of electric current from the metal into the solution and back again. (2) The solution and the metal must be capable of conducting some electricity. (3) A driving force or electric potential must set up the current flow. This potential is usually set up through *ionization*.

**7.3. Ionization.** When a metallic atom dissolves in an aqueous solution, it gives up one or more of its electrons and the charge remaining

is positive. This residual part of the atom carrying a positive charge is called an *ion*, and the solution in which the ions exist is called an *electrolyte*.

When a metal capable of existing in a solution as ions is placed in water or some other dissolving agent, part of the metal will pass into the solution as ions carrying a positive charge, so the remaining metal will be charged with an equivalent negative potential. The potential difference between the metal and the solvent is the driving force which determines the metal's initial tendency to corrode.

This *solution potential*, or *solution pressure* as it is sometimes called, is a characteristic of the metal at a specified concentration of its ions in the solution, and it will vary as that concentration is changed. Therefore it is necessary to measure the potential at some standard concentration if this characteristic is to be compared with that of another metal. When this is done, the electrode potential series in Table 7.1 results. A hydrogen electrode was used as a reference point, and the potentials measured between the metal and hydrogen are shown. The negative electrode metals form positive ions and leave the remaining

TABLE 7.1.<sup>1</sup> ELECTRODE POTENTIAL SERIES

	<i>Element</i>	<i>Symbol</i>	<i>Potential diff., volts</i>
Electrode negative to hydrogen	Potassium	K	-2.92
	Calcium	Ca	-2.76
	Magnesium	Mg	-1.55
	Aluminum	Al	-1.33
	Manganese	Mn	-1.10
	Zinc	Zn	-0.76
	Chromium	Cr	-0.557
	Iron	Fe	-0.441
	Cadmium	Cd	-0.401
	Cobalt	Co	-0.290
	Nickel	Ni	-0.231
	Tin	Sn	-0.136
	Lead	Pb	-0.122
Hydrogen		H	0
Electrode positive to hydrogen	Antimony	Sb	+0.1
	Bismuth	Bi	+0.226
	Copper	Cu	+0.344
	Silver	Ag	+0.798
	Mercury	Hg	+0.799
	Gold	Au	+1.36

<sup>1</sup> International Critical Tables, Vol. 6, McGraw-Hill Book Co., 1929.

metal negatively charged. These metals tend to displace hydrogen from the solution. The positive electrode metals also tend to dissolve, but more feebly.

Water,  $\text{H}_2\text{O}$ , dissociates into positive hydrogen ions ( $\text{H}^+$ ) and negative hydroxyl ions ( $\text{OH}^-$ ). A water solution (the electrolyte) will thus contain H and OH ions as well as ions from any dissolved acids, alkalies, and salts. Acids dissociate into positive hydrogen ions and negative ions of the nonmetallic radical.



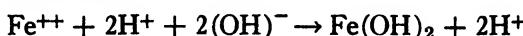
Alkaline solutions dissociate into hydroxyl ions and positive ions of a metal or metal-like radical.



Salts dissociate into ions not containing H or OH.



**7.4. Single Metal Corrosion.** Before a metal is added to a water solution, the solution will be electrochemically neutral, that is, the total charge of positive ions will be equivalent to the total charge of negative ions. The addition of metal ions upsets this neutrality; and to restore equilibrium, a natural tendency of chemical action, either ions of negative potential must be added from another source, or positive ions must be displaced from the solution. In corrosion cells the latter action takes place because there is no other ion source, and displaced ions may be those of another metal (from the salt) or, more frequently, those of hydrogen. For example



The higher the metal in the electrode potential series, the greater its tendency to displace hydrogen. The displaced hydrogen ions will migrate to the metal, take up the residual negative charge, and re-establish equilibrium. The area which receives the hydrogen is called the *cathode*; for single metals in an electrolyte, it may be adjacent to the *anode*, the area at which the metal is dissolving. The "plating" of a film of hydrogen on the metal, however, obstructs the reaction (a) by insulating the metal from the solution, and (b) by the tendency of the atomic hydrogen in the film to re-enter the solution, thus opposing the tendency for the metal to dissolve.

If the corrosion is to proceed, the atomic hydrogen film or "plate" must be removed. This removal, or *depolarization*, can proceed by

either of two methods: (1) changing the atomic hydrogen to the molecular form which escapes as bubbles of gas, or (2) combining the hydrogen with free oxygen in the solution to form water.

The voltage required to cause atomic hydrogen to combine in molecules depends upon the ion concentration in the electrolyte. Table 7.3 shows such data, but they apply only to a standard blackened platinum electrode. Most other electrodes require an even greater negative voltage, and the difference between the voltage required for blackened platinum and that for another material is the *hydrogen overvoltage* of that material.

Table 7.2 is a list of metals in decreasing order of their hydrogen overvoltage. Zinc, at the top of the list, will resist corrosion even by moderately strong acids if oxygen is excluded, because of the difficulty with which hydrogen gas (molecular) forms on the surface.

TABLE 7.2.<sup>1</sup> OVERTOLVAGE SERIES

Zinc	Lead	Cobalt
Mercury	Chromium	Nickel
Magnesium	Gold	Platinum
Cadmium	Copper	Carbon
Aluminum	Silver	
Tin	Iron	

<sup>1</sup> The position of the metals in this series varies to some extent with the electrolyte used in making the tests and with the electrode current density.

**7.5. Two-Metal Galvanic Cells.** The simplest form of the two-metal galvanic cell consists of two metals connected with each other and immersed in a single solution (see Fig. 7.1). In operation, the individual solution pressures cause each metal to dissolve in the solution, and hydrogen is plated on both metals. When oxygen keeps both surfaces depolarized and only one metal is corroded, the amount of corrosion is approximately the same as would result from corrosion of a single metal having the same total surface area. Fig. 7.2 shows the corrosion of clean steel and a steel-copper cell in thoroughly aerated tap water. After a few days the weight loss per unit of time becomes essentially the same for the steel as for the steel-copper cell. The depth of penetration in the steel of the steel-copper cell would be greater than for steel alone because the same amount of metal is corroded from a smaller area. In other words, *the smaller the anode compared with the effective cathodes, the greater the penetration or pitting.*

The rate of corrosion at the anode will be greater if molecular hydrogen can form on the cathode metal. The rate also increases with the separation of the metals in the galvanic series. In addition, low hydrogen

overvoltage is conducive to the formation of molecular hydrogen, so contact between iron and carbon (lowest in the H overvoltage series), as occurs in gray and malleable cast irons and in graphited steam packings, gaskets, etc., will increase the rate of corrosion. The galvanic cells set up between a metal and slag inclusions or scale, corrosion products, etc., on the surface may act in the same way. This is the reason some metals show better corrosion resistance when they are of great purity and when their surface is clean and smooth.

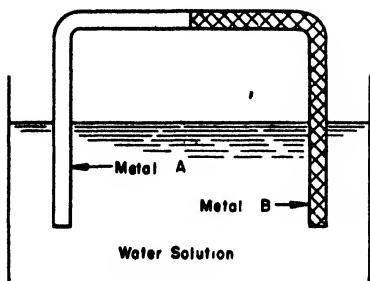


FIG. 7.1. Simple two-metal galvanic corrosion cell.

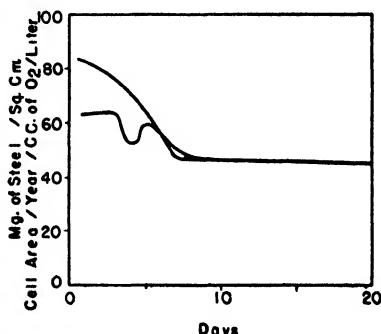


FIG. 7.2. Corrosion of clean steel and a steel-copper cell of the same total surface area in thoroughly aerated tap water.

**7.6. Concentration Cells.** In concentration cells the potential or driving force is caused by differences in the solution in contact with adjoining areas of the same metal surface. The solutions may be of different substances, or merely two solutions of a single substance which vary in acidity, alkalinity, or oxygen concentration. Such cells may set up potentials of the same order of magnitude as those of the two-metal cells.

When solutions of two different substances set up the cell, the anode solution is the one which dissolves the metal. The cathode solution releases the positive ions which are "plated" on the cathode region. When concentration cells are formed by two solutions of the same substance, the metal in contact with the more dilute solution is anodic.

The precipitation of layers of insoluble corrosion products which are not continuous or impervious may also set up such cells by preventing free contact with fresh solutions at the anode area. Once started, these cells tend to be self-perpetuating because the poor contact at the anode gets poorer, thus providing a greater electrical potential.

A simple oxygen concentration cell is set up within a drop of water

such as might condense on an iron or steel plate. As the oxygen in the drop is used, more oxygen enters from the free surface of the drop. But the distribution of oxygen becomes uneven, the concentration being greatest at the outer edge. A cathode is thus established near the boundary of the water drop, and surrounding the anode (where corrosion occurs) at the center of the drop.

The nature of the action going on in the drop can be demonstrated by using a drop of ferroxyl indicator, which is a mixture of water solutions of phenolphthalein, potassium ferricyanide, and sodium chloride. The phenolphthalein in the indicator turns pink in the presence of excess hydroxyl ions, and the potassium ferricyanide turns blue in the presence of excess ferrous ions. A trace of salt solution (sodium chloride) is added to make the corrosion proceed rapidly enough for a good demonstration.

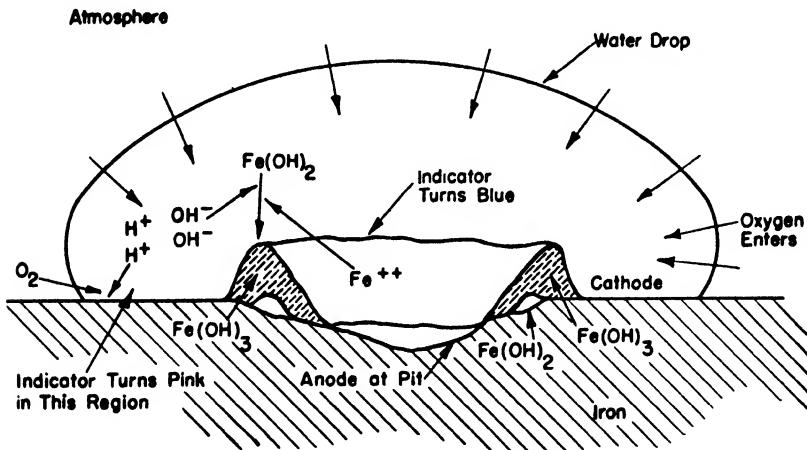


FIG. 7.3. Oxygen concentration cell set up by a drop of water. The action involved is indicated by a ferroxyl solution.

When a drop of the solution is placed on the iron surface, the oxygen concentration at the center of the drop is quickly reduced and a concentration cell is set up. The center of the drop (anode) turns blue, and the edge of the drop (cathode) turns pink. The colors will be best defined if a polished metal specimen is used. In time, the ferrous hydroxide,  $\text{Fe}(\text{OH})_2$ , forms in the solution, then is oxidized to the brown ferric hydroxide  $\text{Fe}(\text{OH})_3$ , and precipitates around the anode as common rust, Fig. 7.3. The deposit of corrosion products around the anode acts to exclude oxygen even more completely from the center of the drop and thus increases the electrical potential of the cell. In

addition, the deposit of ferric hydroxide excludes oxygen from the metal beneath it and forms another oxygen concentration cell. Since the rust which has been deposited acts as a permeable membrane to the electrolyte, permitting some flow of ions, a small amount of green ferrous hydroxide,  $\text{Fe(OH)}_2$ , forms under the heap of rust. If the cell operates for a long enough time, a pit will be formed at the center of the drop.

The mechanism of pit formation on a large surface in contact with water, e.g., a boiler or tube surface, depends upon a break in the surface scale, a deposit of foreign particles, or some similar means to start an anode. After the cell is established, it may form a permeable membrane of corrosion products over the pit, and the material beneath the pit will be the green ferrous hydroxide,  $\text{Fe(OH)}_2$ . If oxygen is not present, as in a closed hot water heating system, only the ferrous hydroxide,  $\text{Fe(OH)}_2$ , can form, and that only to a limited degree.

An interesting example of concentration cell corrosion occurs on iron or steel parts such as posts which are in contact with water and air simultaneously. When the water is steady, pitting results just below the waterline. The usual explanation is that the extra concentration of oxygen at the free surface causes that area to be cathodic with respect to an area under the surface and the resulting concentration cell then causes corrosion at the latter area. The action is no doubt influenced and accelerated by semiprotective corrosion deposits which form near the surface and slide down over the anodic areas, further limiting the oxygen concentration. If the level of water is constantly changing, as with waves and tides, the corrosion will be greatly accelerated over the entire wetted surface, mostly because of the direct exposure to oxygen.

**7.7. Factors Influencing Corrosion.** In electrochemical corrosion of a single metal, such as occurs in acid pickling, the entire surface will be uniformly corroded. For such cases, the rate of corrosion in terms of weight of metal removed per unit area in a unit time gives a true picture of the effect of corrosion, and suitable allowances in thickness may be made to assure the required life.

Often corrosion will not be uniformly distributed over the exposed surface area, but instead will be confined to a localized region, e.g., in a concentration cell. Although the metal removed may be but a small fraction of the whole, this may cause deep pits which can seriously reduce strength and even cause perforation. The rate of corrosion defined above should therefore be considered in the light of the factors which tend to localize the corrosion.

The factors which determine the rate of corrosion will be discussed in the following sections, and those tending to localize the corrosion

will be noted. For convenience, the important characteristics of the metal are discussed first, and those of the environment second.

**7.8. Influence of the Metal.** The effects of electrode potential and overvoltage of hydrogen have already been discussed and will not be reviewed here. Other factors of major importance are:

(1) The chemical and physical homogeneity of the surface. This is important because local differences will set up galvanic cells. Examples of nonhomogeneity include:

(a) *Differences in composition*: either two metals in close contact, discontinuous coatings, two or more alloy phases, segregation, or lamination. An important example of corrosion of two alloy phases is *dezincification* which derives its name from the electrochemical removal of zinc from brasses. The action is a combination of a galvanic cell, which removes the zinc and plates the copper at a cathode, and a concentration cell, which replates the copper back on the original anode in spongy, weak "plugs." The phenomenon has also been encountered in aluminum bronzes, cast irons (iron and graphite), and other alloys containing elements with widely different electrochemical potentials.

(b) *Inequalities in elastic stress* at the surface due to heat treatment, cold working, or applied load. This type of corrosion is called *season cracking* or *corrosion cracking*. It has been found to occur in high-zinc brass and Monel metal which have been cold worked, whereas the annealed metals in the same environment were not attacked.

(c) *Differences in surface finish*: presence of scale, roughness, etc.

(2) The ability of the metal to form a protective film on its surface. This characteristic has been of great importance in industrial applications. Unfortunately, films are formed on only a few metal-alloy groups such as aluminum, chromium, silicon, and chromium bearing "stainless" steel. Soon after the corrosion of these metals has started, such an impervious film is formed that corrosion may be stopped completely. Fig. 7.4 illustrates how the rate of corrosion of two chromium bearing steels is reduced with the formation of the protective film. If it is desirable to form this protective film before the part is actually put into service, a controllable corrosion treatment called *passivation* is used. Most of the protective films are

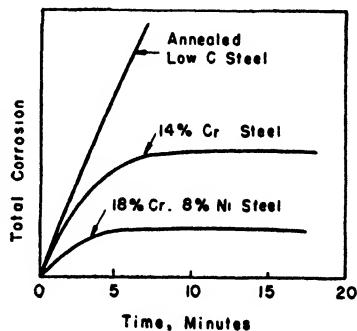


FIG. 7.4. Corrosion of two chromium bearing steels compared with low-carbon steel. Note reduction of corrosion rate with the formation of a protective film.

oxides, so the passivation treatment usually requires an oxidizing solution.

**7.9. Influence of the Environment.** The environment is especially important in determining the ultimate rate of corrosion, but the effect of the many conditions of an environment are difficult to evaluate completely.

Each corrosion problem must be handled individually because factors governing corrosion in one case may be negligible in another. Those factors which are most often of importance are discussed under the headings (1) electrolyte, (2) depolarization, (3) corrosion products, and (4) duration of exposure.

(1) *Electrolyte.* Electrochemical corrosion has been shown to depend on the displacement of hydrogen ions from solution. Since the deposition of ions is favored by high concentrations, it follows that the corrosion rate is increased with hydrogen ion concentration, all other things being equal.

One characteristic of aqueous solutions is that the product of the H and OH ion active concentrations is a constant, which, at room temperature, is approximately  $10^{-14}$  gram mols<sup>1</sup> per liter of solution. Pure water is electrochemically neutral so it must have an equal number of H and OH ions, or  $10^{-7}$  gram mols per liter of each. Acids dissociate into H ions, so acid solutions must have more than  $10^{-7}$  mols per liter of H ions. Alkaline solutions would likewise have more than  $10^{-7}$  mols per liter of OH ions. For convenience, the H ion concentration is expressed as

$$\text{pH} = \log_{10} \frac{1}{\text{H ion concentration (mols per liter)}}$$

For the relationship between pH and H ions, see Table 7.3.

**ACIDS.** The acids may be divided into three classes according to their action in corrosion processes.

(a) *Strong, nonoxidizing acids*, such as hydrochloric and sulphuric, depend upon an external oxygen supply for depolarization. Concentrated hydrochloric and sulphuric acids have low oxygen solubilities and ionize very little. Consequently they are not as corrosive as solutions of moderate concentration on metals which must be depolarized by oxygen.

(b) *Weak acids*, found in foods and soils, could corrode as fast as the

<sup>1</sup> A gram mol (or gram-molecular weight) is defined as a weight in grams equal to the molecular unit weight of the substance. A gram mol of H<sub>2</sub>O is, therefore, 2 + 16 or 18 grams.

TABLE 7.3. ION CONCENTRATION

<i>Potential of hydrogen<sup>1</sup> on saturated platinum plate</i>	<i>pH</i>	<i>Concentration, gram mols per liter</i>	
0	0	1.	$H^+$ ions or acid solution.
-0.058	1	0.1	
-0.116	2	0.01	
-0.174	3	0.001	
-0.232	4	0.0001	
-0.290	5	0.00001	
-0.348	6	0.000001	
-0.406	7	0.000001	$H^+$ and $OH^-$ ions or neutral solution.
-0.464	8	0.000001	$OH^-$ ions or alkaline solution.
-0.522	9	0.00001	
-0.580	10	0.0001	
-0.638	11	0.001	
-0.696	12	0.01	
-0.754	13	0.1	
-0.812	14	1.	

<sup>1</sup> Voltage required to form molecular hydrogen on a blackened platinum plate. For most other metals the voltage required is greater and the difference between the voltage required for other metals and that given above is the *hydrogen overvoltage* of the metal.

strong acids if enough oxygen were supplied, but usually there is little oxygen in places where they occur.

(c) *Oxidizing acids*, such as nitric and chromic, supply their own oxidizing agent, and keep the metal surface depolarized. Therefore, metals cannot be used in contact with oxidizing acids unless a protective film is formed (passivation).

**ALKALIES.** Corrosion by alkalis is generally not as fast as by neutral and acid solutions because the hydrogen ion concentration is reduced, and because the hydroxides produced by corrosion are insoluble up to a certain value of alkalinity. Zinc and aluminum hydroxides, for instance, become soluble around  $pH = 12$ . Ferrous hydroxide is still insoluble in a sodium hydroxide solution at  $pH = 14$ . Increasing  $pH$  therefore reduces the corrosion rate unless the solution becomes alkaline enough to dissolve the protective hydroxide coating.

**SALTS.** The action of salt solutions depends upon the solubility of the corrosion products formed. The chlorides, sulphates, bromides, and fluorides are quite soluble and tend to be very corrosive. The silicates and carbonates are less soluble and protect the metal surface, unless local concentration cells are set up.

Sea water contains fairly large concentrations of chlorides and sul-

phates of sodium and potassium, which form soluble corrosion products and increase corrosion.

**ATMOSPHERIC CORROSION.** The earth's atmosphere contains more oxygen than can take part in corrosion, but the quantity of water and carbon dioxide will vary with climate. Water can be absorbed from the air at less than 100 per cent humidity by many corrosion products. The average humidity below which no absorption occurs is:

<i>Corrosion products of</i>	<i>Relative humidity</i>
Copper	100
Nickel	85
Iron	65

Chlorine compounds are present near sea water, but are at very small concentrations 5 or 10 miles from the sea. Sulphur compounds released mainly by modern fuels make the atmosphere in industrial areas particularly corrosive.

Dust particles from the air can form oxygen concentration cells by limiting the diffusion of oxygen to the metal.

**SOILS.** The corrosivity of soils varies with the locality because of differences in soil texture, acidity, oxidizing agents, moisture content, and temperature. Sulphur and sulphur compounds are present in decaying matter, natural springs, and natural gases and oils, and these compounds are particularly harmful. Hydrogen sulphide depositing bacteria may also be active in certain regions where the soil is free of oxygen and contains organic compounds and sulphates to support the life of the bacteria. Much work has been done on determining the effect of various types of soils and protecting metals, particularly pipes and conduits, for service in them.<sup>1</sup>

(2) *Depolarization.* In neutral and alkaline solutions, hydrogen films are removed mainly by depolarization of the hydrogen with oxygen. Absence of oxygen in the solution will therefore usually cause slow corrosion for neutral and alkaline electrochemical cells, but it will have little effect on corrosion by strong acid solutions since such acids do not usually dissolve very much oxygen. Consequently, unless a protective film is formed, the following factors will be important in determining the rate of hydrogen removal and the rate of corrosion in neutral and alkaline cells.

(a) The concentration of oxygen in the solution as a whole, which is affected by temperature, presence of other dissolved substances, area

<sup>1</sup> See "Corrosion in Soils," LC-689, United States Department of Commerce, National Bureau of Standards, Washington, 1942.

of the corroding solution in contact with air, and actual humidity of the air.

(b) The diffusion of fresh electrolyte through protective metal coatings, which depends upon their porosity.

(c) The flow of the solution which renews the oxygen supply in the metal region. This is affected by convection, temperature, external agitation, depth of immersion, viscosity, etc. Flow or agitation also increases corrosion by wiping the atomic hydrogen and even certain protective films from the surface.

Besides the above effects, solution flow is also important because of the formation of concentration cells. Areas shielded from the solution by foreign particles, cracks, seams, etc., are likely to set up such cells, causing localized corrosion at these areas.

(3) *Corrosion Products.* Corrosion products as well as materials in the corroding medium can form a protective film on the surface of a metal. In cases of passivation discussed previously, this film is extremely thin, but other coatings may be of substantial thickness. When such films are impermeable, they reduce corrosion, but if the film or coating is irregularly distributed and is cathodic to the metal, then a galvanic cell will result and corrosion will be accelerated in adjacent areas. Porous coatings make the underlying metal more anodic by exclusion of oxygen (oxygen concentration cell) and thus accelerate local pitting.

Solutions which are quiescent may increase in OH ion concentration next to the metal as the H ions are removed, and this more-alkaline solution may act as a buffer to limit corrosion or hasten the formation of protective coatings.

(4) *Duration of Exposure.* When a metal is exposed to corrosive media for a long period, its rate of corrosion may change with time. If the corrosion is uniform over the surface (single-metal corrosion), the initial rate is usually much higher than the final rate. If life expectancy is long and the corrosion factors are invariant, design should be based on the final rate.

In localized corrosion, the rate of pitting, contrary to the above, may actually be increased with time by formation of galvanic and concentration cells. Factors which assist the formation of these cells must be controlled or their effects must be estimated in designing for suitable life under these conditions.

When vibration is present in the environment, the simultaneous action of corrosion and alternating stress may cause *corrosion fatigue*. Apparently, corrosive attack causes a small pit and the applied load sets up a stress concentration at the base of this pit. This concentra-

tion of stress acts in the same manner as mechanical stress raisers in reducing the fatigue strength. Under the continuing action of corrosion there can be no final endurance limit.

Repeated cleaning, as by abrasion, removes the corrosion products, and thus lessens corrosion by eliminating the galvanic and concentration cells set up by these products. Railroad rails, for instance, show more corrosion when idle than when in normal use.

#### CORROSIVE BEHAVIOR OF COMMON METALS AND ALLOYS

The multitude of metals and alloys available to the designer, and the equally large number of corrosive environments, make it impossible in this section to give recommendations for specific applications. To do so would require a full knowledge of *all* the requirements, and even then it might be difficult to predict accurately the rate of corrosion and the degree of localization. One needs only to note the apparent disagreement of many recorded data on corrosion resistance taken in both the laboratory and the field to appreciate the necessity for determining very accurately the influence of the many factors that may be involved.

In so far as comparison with similar cases can be used as a basis for choosing materials, Table 7.4 and the following discussion may be used for estimating the resistance of many common metals and alloys to a number of common corrosives. The reader is cautioned to temper these general considerations in response to the factors already discussed. In large installations or for large production, it would be preferable to use this as a guide to conducting pilot tests which assure the necessary life.

**7.10. Iron and Steel.** Under this heading are included cast iron, wrought iron, low carbon steel, and low alloy steel. From the standpoint of corrosion resistance, these metals (with a few exceptions) do not differ markedly; neither do they have superior corrosion resistance, since they were not developed for that purpose.

In water free from dissolved salts, the effect of acidity on the corrosion rate for iron is shown by Fig. 7.5. The diagram may be divided into three separate zones.

(1) The acid zone for  $\rho\text{H}$  less than 4.3. The corrosion decreases rapidly with increasing  $\rho\text{H}$  in this zone. Total acidity, rather than hydrogen ionization alone, determines the  $\rho\text{H}$  limit. Since the formation of molecular hydrogen controls the rate at which the corrosion proceeds, those factors which influence hydrogen overvoltage (surface finish, impurities, metal composition, solution velocity) are of importance. Surface films are of little protection.

(2) The neutral zone for  $\text{pH}$  between 4.3 and 10 (lower curve). In this zone the corrosion rate is medium and essentially constant since oxygen depolarization is the controlling factor. Conditions favorable to increasing the oxygen concentration in the solution widen this zone.

(3) The alkaline zone for  $\text{pH}$  greater than 10. Here the corrosion is slow and decreases with increasing alkalinity ( $\text{pH}$ ). Presence of a protecting hydroxide film is the controlling factor rather than the decreased H ion concentration, since the plating of hydrogen on the metal

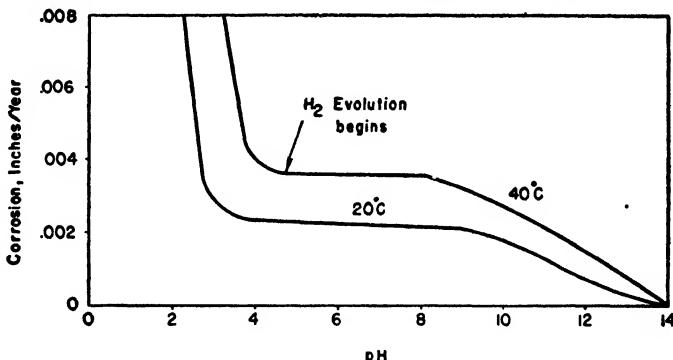


FIG. 7.5. Corrosion rate of iron and low-carbon steel versus hydrogen-ion concentration.

would still occur faster than its depolarization with oxygen. If the solution is very quiescent and contains little oxygen, the alkaline zone may extend to lower values of  $\text{pH}$ . Dissolved salts also change the  $\text{pH}$  limit of this zone.

Ordinarily iron and steel are attacked by all low  $\text{pH}$  acids, but the formation of insoluble ferrous sulphate gives the metals some protection from concentrated sulphuric acid. The formation of ferrous hydroxide accounts for the resistance of the irons and ordinary steels in alkaline solutions. But the dissolved oxygen present will oxidize this hydroxide to ferric hydroxide in the neutral and slightly alkaline solutions, with the formation of the familiar brown rust precipitate. Rust is not protective and in fact aids the formation of concentration cells by limiting diffusion of oxygen to the surface, thus causing pitting. This action is inhibited to some extent by the formation of lime scales and phosphate coatings (both of which are protective) from natural or treated waters. Exposure of cast irons to dilute solutions gives rise to a type of corrosion known as *graphitic corrosion*. This phenomenon was discussed in Sec. 7.8.

Caustic embrittlement is a type of corrosion which may occur when

TABLE 7.4. RELATIVE CORRODIBILITY

Class of Material	Maximum safe temp. for good service, F			Fruit, vegetable juices	Dairy products	Other food products	Acids, moderate concentrations, 5 to 15%					Alkalies 8%
	Oxidizing gases	Reducing fuel gas	Sulphur-rich gas				HCl	H <sub>2</sub> SO <sub>4</sub>	HNO <sub>3</sub>	Acetic	Phosphoric	
Low carb. steel, open-hearth iron or wrought iron	800	..		P	P	P	P	P	P	P	P	E
Copper steel	800	..		P	P	P	PF	F	P	P	P	E
Cr-Cu-Si steel	..											
Hot galvanized iron and steel	1600	1600	1600	P	P	P	P	P	P	P	P	P
Calorized iron and steel												
Gray cast iron	700	..		P	P	P	P	P	F	P	P	G
High silicon iron	..			G+			F	E	F	G	G	E
Nickel cast iron	..	..		F			FG	FG	G	..		GE
Ni-Cr-Cu cast iron <sup>1</sup>	..											GE
Chromium cast iron	1800	1800	1800									.
Nickel steel:												
Low nickel	840	..		P			P	P	P	P	.	E
High nickel	930	..		F	P	..	FG	G	F	P	.	E
Chromium steels:												
4 to 6% chromium	1200	1200	1200	P			P	P	P	P	P	G
12 to 14% chromium	1400	1400	1400	G			PP	PP	GG	G	F <sup>2</sup>	E
16 to 18% chromium	1600	1600	1500	G	G	E	P	P	E	F	P	G
25 to 30% chromium	1900	1900	1800	E	G		P	P	E	F	G	
Chromium-nickel steels:												
8-20%	1600	1600		G			P	G	F	G	G	G
18-8%	1550	1550	300-1300	E	E	E	P	P	G	G	G	E
18-8%, 4% Mo	..	..	..	..	..	..	P	..	G	G	G	G
18-12%							P	F	G	G	F	E
18-35%	1900	1900	1900	G			PP	GP	GG	GG	FF	GG
25-12%	2100	..	..	G	E	E	P	P	F	GG	FG	G
26-24%	2100	2000	..	G	E	E	P	P	F	GG	FG	GG
Sulchrome steel	1500	1500		F	E	..	P	P	E	G	..	GE
Stellite	2000	2000		E	E	GE	F	G	E	G	E	E
Commercially pure nickel	1300	2000	P	FG	EG	GE	F	G	G	E	G	E
Nickel alloys:												
Monel metal	900	2000	P	G	FE	FG	FG	G	P	G	G	E
Nichrome 60-15%	1475	2100	P	..	E	E	F	F	F	G	G	G
Inconel, 14% chromium	2000	2000	..	EG	E	E	F	G	P	G	G	E
80-20% nickel-chromium				E	G	G	FG	G	G	G	E	E
Hastelloys	..	..	..	E	G	G	G	G	G	G	E	E
Commercially pure copper	..	..	..	FG	P	F	F	FG	P	FG	FG	FG
Copper alloys:				FG	P	P	P	FG	P	FG	FG	P
Red brass	..	..	..	FG	P	P	P	F	F	FG	FG	P
Tobin bronze	..	..	..	P	P	F	P	FG	P	FG	FG	F
Phosphor bronze	..	..	..	G	P	P	F	G	P	FG	FG	FG
Silicon bronze	..	..	..	FG	P	..	P	FG	P	FG	FG	FG
Aluminum bronze	..	..	..	G	P	..	F	G	P	FG	FG	FG
Nickel silver	..	..	..	FG	P	..	P	G	P	G	G	G
Admiralty metal	..	..	..	FG	..	..	FG	P	FG	FG	FG	P

## LEGEND

<sup>1</sup> Alloys added should be increased with thickness of section.<sup>2</sup> E at low and P at high concentrations.

P = Poor.

F = Fair, only to be used in temporary construction.

G = Good, will give good service.

E = Excellent, almost unlimited service.

## OF UNCOATED METALS AND ALLOYS

Salt solutions, moderate concentrations			Hot Sul- phite liquor	Dye liquor	Refinery Crudes below 400 F		Atmos- phere		Water					
					Sweet	Sour	Sea shore	Indus- trial	Domes- tic	Mine	Sea	Saline with H <sub>2</sub> S	Brack- ish with NaCl	Wet steam
NH <sub>4</sub> Cl	MgCl <sub>2</sub>	MgSO <sub>4</sub>												
P	F	F	P	P	F	P	P	F	P	F	P	P	F	F
P	P	PF	P	P	FG	FG	G	F	F	FG	F	F	F	FG
..	..	..	P	P	FG	FG	G	G	P	F	P	..	..	..
P	P	P	P	P	F	F	E	E	P	P	F	F	F	F
G	G	G	P	P	F	FG	E	E	E	F	F	F	F	..
F	F	F	F	F	G	FG	E	GE	F	G	FG	G	G	..
P	F	G	F	G	..	..	F	E	F	G	F	G	G	..
F	G	G	G	G	..	..	E	E	G	FG	E	G	G	..
P	GG	E	P	P	G	E	GG	GG	FG	FG	FG	G	F	FG
G	GE	E	P	F	E	E	G	G	G	G	GG	..	GG	GGE
E	E	E	GE	F	G	E	E	E	G	G	G	E	E	E
..	..	..	G	P	..	E	E	E	E	E	FG	GG	E	E
E	E	E	GE	G	E	E	EE	EE	E	E	G	GG	G	E
..	..	..	..	..	PG	..	..	GG	E	E	F	F	F	F
E	E	E	G	G	E	E	E	E	E	E	E	E	E	E
E	E	G	P	P	E	F	E	GG	E	E	PG	E	G	E
..	..	..	..	..	..	..	..	GG	G	E	G	G	..	..
G	G	G	E	G	G	G	E	E	E	E	G	E	E	E
..	..	F	FG	..	..	G	G	G	G	FG	G	P	..	G
..	..	F	FG	..	..	G	FG	..	FG	FG	G	F	F	P
..	..	G	FG	..	..	G	GG	..	..	F	GG	..	..	..
..	..	G	FG	G	..	..	GG	G	..	FG	GG	F	..	..
..	..	..	FG	..	..	..	GG	G	..	FG	GG	..	F	..
..	..	..	FG	..	..	..	G	G	..	FG	G	..	F	..

This table has been reproduced from Table XXVII from Corrosion Causes and Prevention by F. N. Speller, McGraw-Hill Book Co., 1935, pp. 142-145, by courtesy of the author and publisher. It is emphasized that this table is intended to give only a very approximate idea of the relative rating of the metals listed.

The various factors arising from different conditions of service should be considered in the light of the discussion in this chapter when estimating the relative advantage of different metals for a given application. The possibility of using protective coatings, corrosion inhibitors, or cathodic protection with lower cost metals should also be considered.

iron or steel is used in contact with sodium carbonate or sodium hydroxide solutions at high pressure. Steam boilers handling such waters sometimes develop cracks in riveted joints below the waterline. They have been associated with the removal of sulphides and oxides by the hot solution and cathodic hydrogen. The cathodic hydrogen apparently causes embrittlement by penetrating the metal and reducing the oxides or sulphides. The vapor thus formed at the grain boundaries causes a bursting pressure which may cause cracking.

For atmospheric exposure, the presence of copper in iron or steel improves the corrosion resistance, probably owing to the formation of a tightly adherent rust.

For handling sulphuric acid and certain other acids, a cast iron of 14 per cent silicon and a trace of molybdenum is sometimes used. These alloys are hard to machine and very brittle, however, so their application is limited. Another cast iron which has improved corrosion resistance contains 20 per cent nickel. This alloy has very good erosion and wear resistance combined with resistance to oxidation at elevated temperatures. In this respect it is not as good as the corrosion resisting steels, and it has the added disadvantage of grain growth. It has good resistance to nonoxidizing acids such as sulphuric, also to hydrogen sulphide and alkaline solutions.

**7.11. Corrosion Resisting Steels.** This group comprises those high chromium steel alloys which were developed primarily for resistance to corrosion. These steels are popularly known as "stainless steels" although, as emphasized in the previous discussion, no perfectly stainless metal has yet been found. In discussing these materials, it is convenient to divide the group into five basic types, as follows.

- I. 12 to 17% chromium steel with high carbon (0.3 to 1.5% C). Used chiefly for cutlery and small parts requiring a hard surface for wear resistance.
- II. 11 to 14% chromium steel with low carbon (0.06 to 0.13% C). Used for structural applications requiring good corrosion resistance.
- III. 16 to 20% chromium steel with low carbon (0.06 to 0.15% C). Used chiefly for ornamental purposes and resistance to oxidation to 1650 F.
- IV. 25 to 30% chromium steel with about 0.25% C. A nonheat treatable alloy used chiefly for resistance to oxidation at elevated temperatures.
- V. 18 to 26% chromium and 8 to 21% nickel steel with 0.06 to 0.15% C. The maximum resistance to corrosion.

The improved corrosion resistance of this class of steels is caused by the formation of a protective film due to the presence of chromium. This film may be formed in air, but frequently it is artificially accelerated by a passivating dip into dilute nitric acid. This dip removes the free iron at the surface of the part and also forms the protective film. If the film is broken in service, it will usually heal if oxygen is present.

The group as a whole is resistant to nitric acid and all but Type I are used in the nitric acid industry. They are resistant to the weak acids but are attacked by the strong nonoxidizing acids, hydrochloric and sulphuric, of all concentrations. Chloride solutions will also break down the protective film and cause corrosion. No general rule can be set down for the resistance to mixed oxidizing and nonoxidizing acids. The resistance to attack by alkalies and organic substances is very good. The resistance of various chromium steels to corrosion by petroleum products is compared with that of plain carbon steel in Fig. 7.6.

In conjunction with the formation of the protecting film, it should be mentioned that the finish is important to the corrosion resistance. *The better the finish, the greater the resistance to corrosion.*

Nickel added to chromium steel, as in Type V, increases the alkaline resistance and improves the resistance to all neutral solution and acid attack.

"Stainless" steels of all the types mentioned are subject to local failure by intergranular corrosion if improperly heat treated. The improper treatment consists in heating the solution-quenched specimen within a critical range from 900 to 1400 F, even for only a few minutes. It is believed that chromium carbides are precipitated on the grain boundaries by this treatment. These carbides rob the adjacent metal crystals of their chromium and thus remove their resistance to corrosion. Consequently, the chromium-impoverished metal along the grain boundaries is readily attacked by strongly corrosive agents. When these alloys are made susceptible to this attack, they are said to be "sensitized." They can be restored to the original condition by reheating to 1900 to 2000 F and quenching in water so as to reabsorb the carbides and retain them in solution.

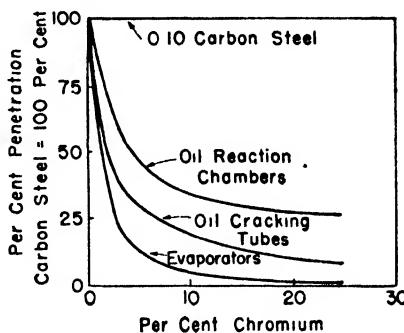


FIG. 7.6. Resistance of various chromium steels to corrosion by petroleum products compared with that of plain carbon steel. (Speller, "Corrosion, Causes and Prevention," McGraw-Hill Book Co., 1935, p. 131.)

An intermediate grade of corrosion resisting steels is formed by those alloys containing 4 to 6 per cent chromium. Although their resistance compared with the above types is small, it is still four to six times that of low carbon steel for corrosion in air and at somewhat elevated temperatures, and may prove the more economical in certain applications, particularly those of the oil industry. They offer considerable oxidation resistance to 1200 F.

Recently, clad metals (e.g., Pluramelt) have been developed to take advantage of the corrosion properties of the stainless steels and the low cost of low carbon steel. These metals consist of a thin sheet of chromium steel on a low carbon steel plate.

**7.12. Copper and Copper-Base Alloys.** From the position of copper in the electrode potential series, it would be expected to have excellent resistance to corrosion. In general, this is true both for copper and for its alloys.

The corrosion of copper, except for a few special cases, differs from that of the other metals studied in that its corrosion resistance depends on its limited solubility and reasonable hydrogen overvoltage rather than on the formation of protective films. Thus the corrosion tends to proceed by depolarization of hydrogen; so the control of oxygen is important in acid corrosion as well as corrosion by neutral waters and alkalies.

For this reason the metal and its alloys, with the exception of the brasses, are fairly resistant to the nonoxidizing acids (sulphuric, phosphoric, etc.) and to many salts and industrial waters of limited oxygen content. And for the same reason they are in general attacked by the oxidizing acids and their salts, since no passivation occurs. Ammonium hydroxide corrodes them easily, but usually they are resistant to alkalies of moderate concentration at normal temperatures.

The red brasses (85 Cu, 15 Zn) are not greatly different from copper and the bronzes in corrosion resistance to dilute acids. The yellow brasses (65 Cu, 35 Zn) are of considerably less value. Yellow brasses are subject to dezincification and corrosion cracking, which have already been described. The presence of 1 per cent tin in the brass will reduce the tendency for dezincification, especially of neutral and slightly acid solutions. Ammonia and industrial ( $\text{SO}_2$ ) atmosphere are quite active in causing corrosion cracking. It is interesting to note that both of these forms of corrosion can be substantially reduced by using red instead of yellow brass. (See Fig. 7.7.)

Corrosion of insulated copper wire is often attributed to the characteristics of the insulation. Rubber insulation and tapes may contain sulphur or acids, and other insulating materials are often capable of

forming acids if they absorb moisture. In any case, the prevention of water penetration is of primary importance when limiting this type of corrosion.

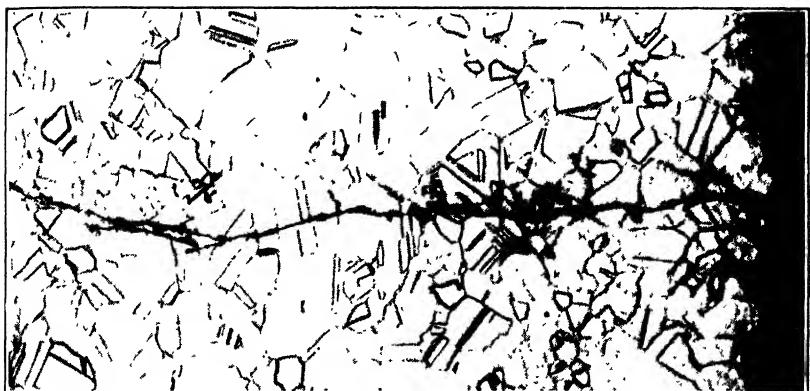


FIG. 7.7. Photomicrograph of season crack in aluminum brass (76 Cu, 22 Zn, 2 Al). Note that the crack is transcrystalline in the body of the material, and intercrys-talline near the edge at the right.

**7.13. Aluminum and Its Alloys.** The corrosion resistance of aluminum is good in nearly neutral waters, atmospheres, and salts, and also in the oxidizing acids such as nitric, because it forms a protective oxide film. In air this film is of the order of 0.000001 in. Strong nonoxidizing acids and strong alkalies will remove this film, and chloride salts will penetrate it, so corrosion in the presence of these solutions will be rapid.

Alloying or metallic contact with even the most noble (cathodic) metals will not produce galvanic cells of importance in weak electrolytes, or industrial and rural atmospheres, but copper, nickel, tin, and to some extent zinc have been found very corrosive in humid sea atmospheres. Normal atmospheres permit contact with zinc and cadmium plated iron surfaces.

Duralumin is subject to intergranular crystallization if aged at much above room temperature. Uniform surface elastic stress seems to promote this condition. Duralumin also has a markedly reduced fatigue strength in corroding conditions. In order to take advantage of the higher strengths it offers and still provide suitable corrosion resistance, Duralumin has been made with a pure aluminum surfacing, and in this form is called Alclad, Pureclad, etc. When Duralumin rivets are used with a clad sheet, the corrosion is limited to a small amount on the sheet near the rivet.

Aluminum may be protected by artificial formation of the oxide film

(anodizing) by plating oxygen on the surface in an electrolytic cell of some oxidizing acid. The oxide thus formed will have a depth of 25 to 500 times that which occurs in air. A cheaper but somewhat less effective oxide coating can be formed by a chemical dip treatment. Painting is also effective.

**7.14. Magnesium and Its Alloys.** Magnesium readily combines with oxygen at low temperatures, forming a protective oxide that makes the metal serviceable for unpolluted atmospheres. Attack by acid phosphates, bichromates, or dilute chromic acid is resisted, but performance in the presence of salt, salt spray, or industrial atmospheres is poor. Presence of manganese improves the resistance to sea water.

In hydrofluoric acid, magnesium base alloys have the ability to form another protective film, and so are used for handling that acid in all but the most dilute concentrations. Resistance to other acids is very low. The resistance to alkali solutions by comparison is quite good.

From the electrode potential series, it is apparent that magnesium should set up powerful electrochemical cells with most any other metal. This tendency is so strong that copper and nickel will prove damaging if present as alloys in the metal at concentrations over 0.1 per cent. The couple with zinc and mercury is considered serviceable, mainly because the smaller difference in solution pressures and the higher hydrogen overvoltage of these metals reduce the corrosion. Thus magnesium can satisfactorily be put in contact with galvanized iron, although contact with aluminum under corrosive conditions is harmful.

If the corrosion resistance of magnesium is to be improved, painting is the only recourse; plating and anodic oxidation are not beneficial.

**7.15. Zinc and Cadmium.** The largest industrial application of zinc is for the galvanizing of iron. Zinc is anodic to iron (see Table 7.1); so in the presence of corrosive media, the zinc coating will corrode first, thus prolonging the life of the iron beneath. This means that discontinuities in its surface do not hasten the corrosion of the metal beneath as would a coat of a more noble (cathodic) metal.

The life of galvanized parts is also increased by the tendency of the zinc surface to form a protective film (oxide or oxycarbonate), particularly under *alternate* wet and dry atmospheric exposure. The alkaline resistance is also enhanced by the formation of a protective film (hydroxide) but at a *pH* of 12 or higher this film dissolves and the zinc corrodes rapidly.

Strong acids (as found in industrial atmospheres) will also attack zinc; but gasoline, grease, anhydrous alcohol, soap, and soap pastes are essentially inert to zinc.

Cadmium is similar to zinc in its corrosive properties and uses, so it

will be included here. The resistance of cadmium to attack by industrial atmospheres, strong acids, and very strong alkalies ranges from 100 to 50 per cent of that of zinc under different conditions. The hydroxide of cadmium is not as soluble as that of zinc, so the cadmium as a plate on iron has longer life in normal alkaline solutions. For underwater exposure, galvanizing is considered better than cadmium plating because greater thicknesses can be used at lower cost. The appearance of cadmium plate, until recently, was superior to that of electrolytically deposited zinc, but recent progress in applying zinc permits bright finishes which retain their luster for a considerable time.

**7.16. Nickel and Nickel-Base Alloys.** Although the position of nickel in the electrode potential series would indicate that it would corrode more than copper, actually the corrosion resistance of these two metals is nearly the same, and in some cases it overlaps. Since nickel is the more costly and least abundant, the choice usually rests with copper or its alloys if they are not unsuited. Applications in which nickel finds greatest use are: (1) the handling of alkalies, and (2) resistance to some nonoxidizing acids.

Hydrochloric acid is resisted by nickel and Monel when in low concentrations. Alloys with molybdenum and iron (Hastelloy A and B) are used for handling hydrochloric acid when no oxidizing agents are present. Chromium is added for good resistance even when oxidizing agents are present. An alloy with either chromium (Illiium) or silicon (Hastelloy D) is used for handling sulphuric acid solutions.

**7.17. Other Metals.** *Lead.* The outstanding application of lead is in the sulphuric acid industry. The metal has been found to form a protective film by contact with that acid, and thus is suitable for withstanding further attack. Lead coatings or sheathings have also been used for protection against weather and corrosive industrial atmospheres, and in the handling of a number of corrosive chemicals.

*Tin.* Tin is used mainly as a protective coating for more noble metals. Because of its poor physical properties and higher cost, it is seldom used in the form of a base metal. Its resistance to the weak acids and neutral solutions is rather good, but it is rapidly attacked by alkaline solutions, especially at elevated temperatures. The main use for tin is in plating cans.

*Silver and Other Precious Metals.* These metals are important to the study of corrosion because of their application to the chemical industry. Silver is perhaps the most used. Some of the applications of it are in handling acetic acid, acetate rayon, food products, e.g., syrups, jams, jellies, etc., photographic emulsions, and in the manufacture of chemically pure chemicals. Frequently the equipment may use the metal

only as a lining, but the high scrap value of parts makes it practical in the long run to use parts made entirely of silver.

**7.18. Methods of Improving Corrosion Resistance.** The various methods that may be employed to lengthen the life or reduce the corrosion of a metal part may be classed under the following headings:

1. Improvement in the corrosion resistance of the metal.
2. Changing the environment so it will be less corrosive.
3. Isolating the metal from the destructive environment.

Under heading 1 is selection of metals which will have good resistance to the particular environment. The previous discussion should facilitate this selection. Perhaps placing insulation between two different metals in contact, thereby destroying the galvanic cells, could also be considered in this class.

Under heading 2 are dehydration, deoxidation, electrolytic cathodization, and use of inhibitors.

When a part in the atmosphere must resist corrosion, methods of dehydration (removing moisture) will be useful, since the electrochemical cell depends on an aqueous solution for its action. Dehydration may be brought about by absorbing all the water present, as with lime, by driving off the moisture with heat, or by preventing the condensation or dripping of moisture on the surface by shielding.

Deoxidation is used to reduce the corrosion in closed conduits, containers, etc. It is effective on those corrosion reactions (particularly those on the anodic metals by dilute acids and neutral and alkaline solutions) which depend on oxygen depolarization. For this purpose especially designed deaerators are constructed and situated so as to remove most all the air in the fluid entering the conduit. The gasoline and oil pumped in pipe lines are deaerated before they are pumped into the line. It should be remembered that deaeration will be very objectionable where the protection of the metal depends on maintenance of a passivated film by continuing oxidation.

Electrolytic cathodization essentially consists in eliminating the driving force of the electrochemical cell by externally applying a counter-potential. It has been used in limiting the corrosion of underground pipes in particularly acid soils.

Pipes are often corroded because of potentials set up in the surrounding earth. Streetcar lines which use the rails as conductors often set up potentials in the soil and cause nearby pipe lines to carry part of the current. Very long pipe lines also carry currents which may originate from galvanic action or from earth currents due to terrestrial magnetism. But whatever the source of the current in a pipe line it is corroded at

the section which acts as an anode. A potential from an external source applied so as to make these sections cathodic will tend to stop corrosion, but it may have an opposite effect upon other pipes nearby.

The use of inhibitors is of major significance in equipment such as steam turbines where a corrosive, such as the lubricating oil, is to be in contact with a metal surface for a long time under optimum conditions for corrosion (elevated temperature, motion, aeration, moisture from condensate, etc.). Inhibitors for this application are of two types: antirust and antioxidant. The antirust inhibitor really is for the purpose of wetting the surfaces of bearings and thus, by excluding moisture, limiting rusting. The antioxidant inhibitor is for the purpose of removing the free oxygen so it will not combine with the oil. Other types of inhibitors are used to treat natural waters used in boilers, pipe lines, etc., so corrosion in them will be limited or avoided.

Under heading 3 are such operations as passivation; plating, clading, and painting; slushing; and evacuating.

Passivation has already been referred to. The oxide coating formed by this process can be accelerated by anodic oxidation or corrosive action with an oxidizing acid.

Plating and clading will reduce the corrosive rate under certain conditions by self-sacrifice corrosion, or by presenting a material which forms a protective film for the environment. The various materials used and the methods of applying them will be discussed in a later chapter. Painting is the most commonly used and one of the cheapest methods of isolating the part from the environment, but for long service it must be renewed. It cannot be expected to withstand an extremely corrosive combination of service conditions.

Slushing compounds may be of two fundamentally different kinds. (1) They may be of polarizing nature, which means they will *drive* the moisture away from the surface, or (2) they may be mere films (e.g., no-oxide grease) which prevent contact of additional corrosive with the metal but *will not* stop corrosion if corrosion products (such as concentration cells) are trapped on the surface. At present only one polar slushing compound is available commercially. Its trade name is Tectyl. Slushing compounds should not be oxidizing in nature, or they themselves will serve as the corrosive if any moisture (even distilled) is trapped by them.

Evacuation consists in building an enclosure around the article which is to be resistant to corrosion, and then evacuating all corrosive media from the enclosure. In some cases it may be necessary only to remove one constituent, say the oxygen, or the moisture. An excellent example of this method is the totally enclosed type of refrigerator unit contain-

ing a compressor, a condenser, and an evaporator, filled with  $\text{SO}_2$ , but no oxygen or moisture.

**7.19. Selecting Metals for Corrosive Applications.** Material may be considered corrosion resistant or not depending on what is expected of it. Four different criteria of corrosion resistance are

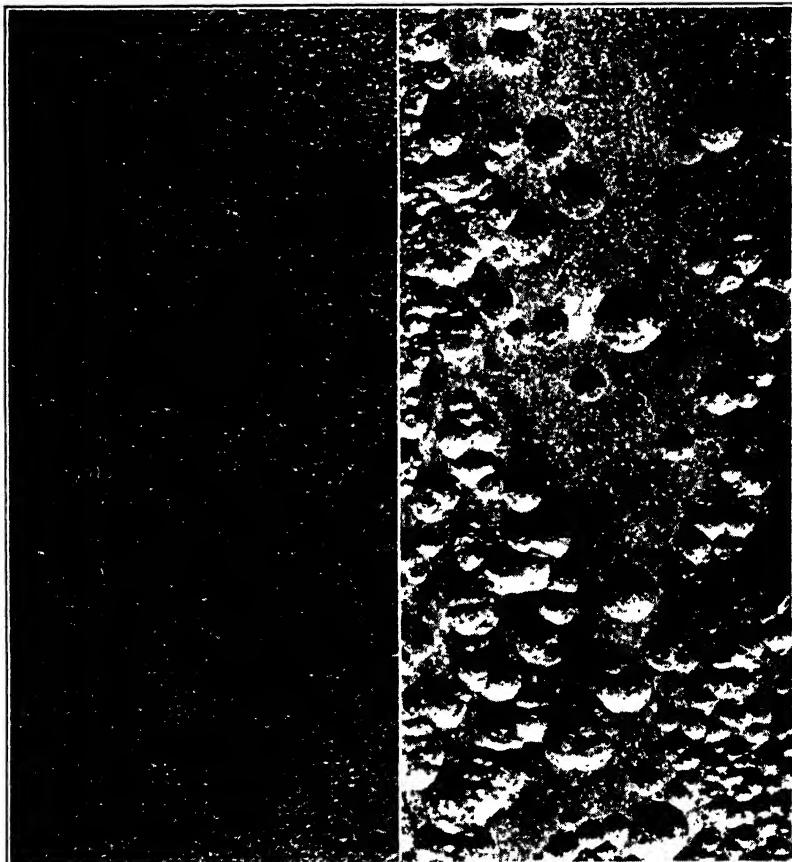


FIG. 7.8. Corrosion of plain carbon steel. About actual size. (*Courtesy Research Laboratories, Carnegie Steel Corp.*)  
Left, uniform surface corrosion. Right, pitting.

(1) maintaining the original surface appearance without staining, tarnishing, or discoloration of surrounding areas; (2) avoiding contamination of such products as foods; (3) preventing leaks of closed containers or conduits; (4) maintaining strength and other original mechanical properties so that the structure will not be weakened excessively.

Factors 1 and 2 were not considered at length because they involve

separate studies in themselves. However, they as well as the other two factors will be the criteria on which the choice of corrosion resistant metals must be based. Counterbalancing these criteria at all times must be the economic estimates of the *ultimate* cost of the apparatus. In certain instances it might be considered good business and sound engineering to use an inferior metal with the expectancy of replacing it during the service life of the entire apparatus. In another case, periodic maintenance such as cleaning, polishing, replating, and repainting may prove more economical than the price of a metal which would have the corrosion resistant properties to give the life without maintenance. In a third case, maintenance and/or replacement of an inferior metal may be far more costly through complaints, loss of good will, risk to life, etc., than the additional cost of the better suited material.

### REVIEW QUESTIONS

1. Is erosion a form of corrosion?
2. Define "ion," "electrolyte," and "electrode potential."
3. (a) What is "depolarization" and by what methods can it be performed?  
(b) Which metals are hardest to depolarize?
4. Name three characteristics of a metal surface which might cause corrosion to be localized.
5. What is *pH*, and how does it influence corrosion?
6. What determines the rate at which each of the three types of acids attacks a metal?
7. In general, do metals corrode faster in acids or in alkalies?
8. Which of the chromium steels is most used for (a) a hard, wear resistant surface, (b) high temperature oxidation, (c) maximum corrosion resistance?
9. What is "sensitized" stainless steel, and how is it produced?
10. Does magnesium give good service when used in a humid atmosphere in contact with (a) aluminum, (b) galvanized iron, (c) copper?
11. What three general methods of approach may be employed to lengthen the life or reduce the corrosion of a metal part?
12. (a) What is the purpose of slushing? (b) How do the two types of slushing compounds differ?

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## CHAPTER VIII

### MAGNETIC PROPERTIES OF MATERIALS

By DR. L. T. RADER

**8.1. The Nature of Magnetism.** All substances can be divided into one of three classes — paramagnetic, diamagnetic, and ferromagnetic — depending on how they react when subjected to a magnetic field. Paramagnetic substances are those which are only feebly magnetic. Diamagnetic substances actually set up fields which oppose applied fields. Ferromagnetic substances are very strongly magnetic and are the substances of greatest practical interest as magnetic materials. They include iron, nickel, cobalt, and some alloys. Some permanent magnets contain paramagnetic materials such as aluminum and silver as alloying elements.

The present day theory of ferromagnetism attributes the magnetic properties of a substance to electron spin. The electron is thought to be spinning about an axis through its own center, in addition to its rotation around the nucleus of the atom. Electron spins and electron charges influence each other by trying to keep the spins parallel in neighboring atoms, while the forces of thermal agitation tend to destroy the lineup. The effect of these electron forces is the formation of small regions, about 0.001 in. cube, known as *domains*. Each domain includes about  $10^{15}$  atoms, but the forces are such as to make this grouping act as a single unit. Ferromagnetic substances consist entirely of such domains, each magnetized in a definite direction. Since ferromagnetism occurs only in crystalline substances, there are six directions, a positive and a negative for each of three Cartesian axes, in which it is relatively easy to magnetize ferromagnetic materials.

The familiar concept of considering magnetic material to be made up of a large number of elementary magnets, or dipoles, is thus seen to be a reasonable physical picture. A domain is in effect such an elementary magnet whose direction will change when a magnetic field is applied.

**8.2. Definitions.** A *magnetic field* is a region in which magnetic forces exist. It is created either by electric currents (in electromagnets) or by permanent magnets. *The field strength, magnetic intensity, or magnetic force is the force which would be exerted by the field on a unit*

*magnetic pole<sup>1</sup> placed at that point.* A common physical concept pictures the field as being filled with lines of induction. The number of lines of induction per square centimeter is usually denoted by the letter  $B$  with the units of gausses. Other terms often used synonymously with lines of induction are lines of flux, maxwells, lines of flow, normal induction, or simply lines, or flux.

The source of the flux is known as the magnetizing force and is denoted by  $II$  with units of oersteds. (The English unit is the ampere-turns/inch.) Since most magnetic material is used in electromagnets, the ASTM defines  $H$  by the equation

$$H = 0.4 \pi nI \quad [8.1]$$

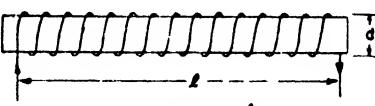
where  $II$  is the magnetizing force in oersteds at the center of a long solenoid,<sup>2</sup> of such length that the end effects are negligible, of  $n$  turns per centimeter, and carrying a current of  $I$  amperes (see Fig. 8.1a). This is also the same as the magnetizing force at the mean diameter of a uniformly wound ring or toroidal solenoid (Fig. 8.1b). The ring solenoid or closed circuit is ordinarily used in testing magnetic materials, and the magnetization data are usually presented by plotting a graph with  $B$  in gausses or in lines per square inch versus  $II$  in oersteds, or in ampere-turns/inch, i.e., flux density versus magnetizing force. If no ferromagnetic material is present,  $II$  and  $B$  have the same numerical value at any point.

<sup>1</sup> A unit magnetic pole is defined as a magnet pole of such strength that it will exert a force of one dyne upon an equal pole at a distance of one centimeter, both poles being in air. This is expressed by

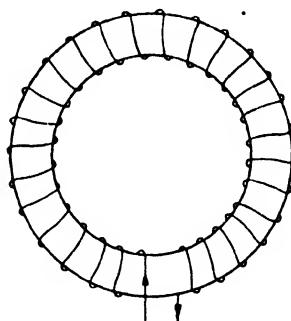
$$f = K \frac{m_1 m_2}{r^2}$$

where  $K = 1$  if units are dynes and centimeters and  $m$  and  $r$  represent pole strength and separation respectively. An isolated unit pole does not actually exist, but it is approximated by a long, needlelike magnet in which the poles are widely separated.

<sup>2</sup> A solenoid whose length is equal to or greater than ten times its diameter is a "long solenoid."



(a) Long Solenoid,  $\frac{L}{d} \geq 10$



(b) Toroid

FIG. 8.1. (a) A long solenoid, with an air core produces a magnetizing force,  $H = 0.4\pi nI$ , at its center. (b) A toroid with an air core produces a field of equal strength.

The total magnetizing force in a magnetic circuit is termed the *magnetomotive force*, and is abbreviated mmf.

**8.3. Magnetization.** A ferromagnetic specimen is unmagnetized when the domains are oriented at random. In such a case there is no net mmf across the specimen and it does not produce any magnetic field outside itself. Thus  $B$  and  $H$  are equal to zero.

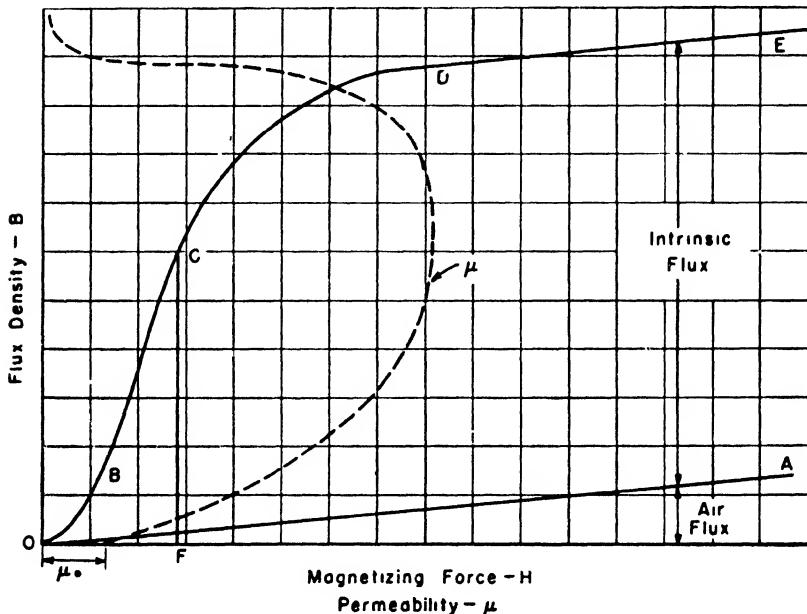


FIG. 8.2. Magnetization curve for a ferromagnetic material. The ratio of  $CF$  to  $OF$  is the permeability at point  $C$ . The dotted line shows the variation of permeability with flux density. The slope of the air flux line ( $OA$ ) is exaggerated for clarity.

Consider a toroidal solenoid wound on a nonmagnetic core, such as is shown in Fig. 8.1b. If the flux density is measured on the center line of the toroid, the relationship between  $B$  and  $H$  is given by the straight line  $OA$  in Fig. 8.2. If now the space within the toroid is filled with an unmagnetized ferromagnetic material, the well-known magnetization curve,  $OBCDE$ , is obtained. The magnetization curve has many names, being referred to as the  $B$ - $H$  curve, the magnetic saturation curve, the virgin curve, or simply the saturation curve.

The increase in flux,  $B$ , in ferromagnetic material occurs when the magnetic field acting on the domains orients them in the direction of the field, so that the mmf of each elementary magnet or domain is in

such a direction as to increase the flux produced by the external field. The straight part of the curve,  $BC$ , is traced out because the domains, influenced by a field, easily turn into those directions of magnetization which have a component in the direction of the magnetizing force. As the magnetizing force increases the domains are with greater difficulty oriented into the exact direction of the field. This gives the rounded part of the curve,  $CD$ , commonly known as the *knee*. The knee is not

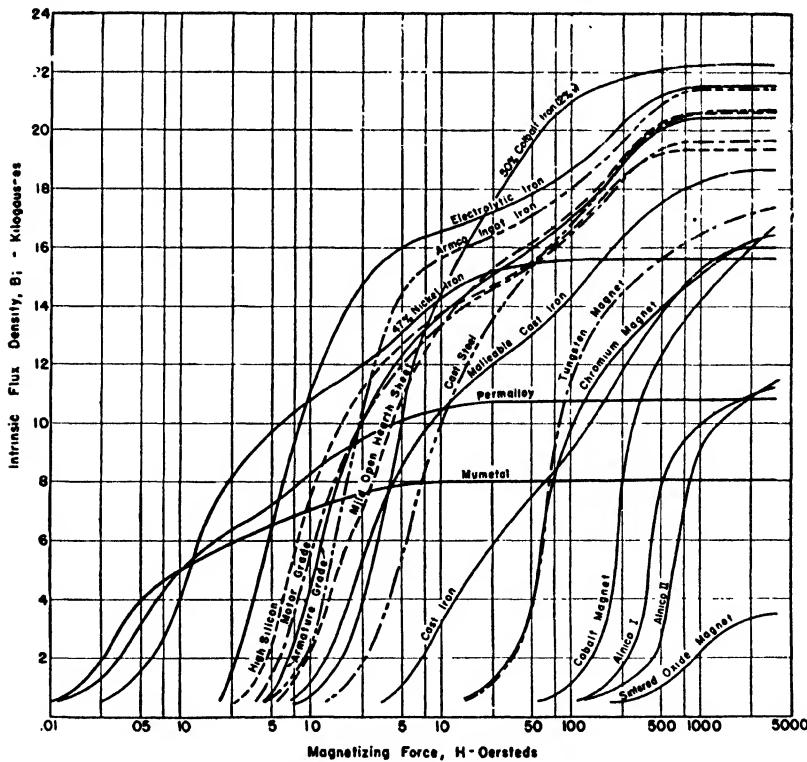


FIG. 8.3. Intrinsic flux density versus magnetizing force for several ferromagnetic materials. The magnetization curve for the permanent magnet materials is actually not important, but is included only for comparison.

usually a very well defined point, except in certain special materials. As the applied current is further increased, the magnetization curve ultimately attains the slope  $DE$ , equal to that of the air line  $OA$ . The material is then said to be *saturated*.

The difference in flux between the saturation curve and the air line,  $OA$ , at any magnetizing force is due to the contribution of the magnetic material. This flux is known as the *intrinsic flux* and gives a truer

measure of magnetic properties than does the total flux, especially at very high mmf's. Many common magnetic materials are compared in Fig. 8.3 by plotting  $H$  on semi-log paper as abscissa and intrinsic flux density,  $B_i$ , as ordinate. The point at which the intrinsic flux density curve becomes horizontal gives the *intrinsic saturation*.

**8.4. Permeability.** Referring to Fig. 8.2, the ratio of the ordinate  $B$  at any point to the abscissa  $H$ , where  $B$  and  $H$  are in metric units, such as  $CF/OF$ , is known as the *permeability*,  $\mu$ . The dotted curve in Fig. 8.2 shows how  $\mu$  varies with flux density. The actual slope of the  $B$ - $H$  curve at any point is called the *differential permeability*.

In terms of this definition, a vacuum or free space has a permeability of unity; a diamagnetic material has a permeability less than unity; a paramagnetic material has a permeability slightly greater than a vacuum and approximately independent of the magnetizing force; and a ferromagnetic material has a permeability which is considerably greater than unity and varies with the magnetizing force. The class of metals lying between paramagnetic and ferromagnetic is often called *feebly magnetic*.

If both sides of Eq. 8.1 are multiplied by  $\mu$ , then

$$\mu H = 0.4 \pi n I \mu = \frac{0.4 \pi N I \mu}{l} \quad [8.2]$$

where  $N$  is the total number of turns and  $l$  is the length of the straight solenoid (or the mean diameter of the toroidal solenoid) in centimeters. Since  $B = \mu H$ , then Eq. 8.2 may be written

$$B = 0.4 \pi N I \frac{\mu}{l} \quad [8.3]$$

In engineering units Eq. 8.3 can be written as

$$NI = 0.313 \frac{B'' l''}{\mu} \quad [8.3a]$$

For a field in air,  $\mu = 1$ , so that  $NI = 0.313 B'' l''$  [8.3b]

where  $NI$  = ampere-turns causing the magnetic field,

$B''$  = flux density in lines per square inch,

$l''$  = length of air gap in inches.

Now the total flux in any area, assuming  $B$  is constant over the area, is  $\Phi = BA$  where  $A$  is the cross-sectional area in square centimeters.

Therefore

$$\Phi = 0.4 \pi NI \frac{\mu A}{l} = \frac{0.4 \pi NI}{\left( \frac{l}{\mu A} \right)} \quad [8.4]$$

**8.5. Analogy with Electrical Circuits.** The quantity  $l/\mu A$  is known as the *reluctance* by analogy with the electrical resistance ( $\rho l/A$ ), so that there is, in effect, an Ohm's law for magnetic circuits which states that

$$\text{Flux} = \frac{\text{Total mmf}}{\text{Reluctance}} = \frac{\mathcal{F}}{\mathcal{R}} \quad [8.5]$$

Comparing the equations

$$\Phi = \frac{\mathcal{F}}{\mathcal{R}} = \frac{\text{mmf}}{\frac{l}{\mu A}} \quad \text{and} \quad I = \frac{E}{R} = \frac{\text{emf}}{\frac{\rho l}{A}} \quad [8.5a]$$

it is evident that

$$B = \frac{\Phi}{A} = \left( \frac{\text{mmf}}{l} \right) \mu \quad \text{and} \quad i = \frac{I}{A} = \left( \frac{E}{l} \right) \frac{1}{\rho}$$

The term  $\text{mmf}/l$  is defined as  $II$ , and  $\mu$  is the permeability of the material under magnetization. This permeability determines what flux density will "flow" under the magnetizing force,  $H$ . In empty space,  $\mu$  is unity, and  $B$  and  $H$ , that is, lines of induction and lines of force, have the same numerical value and the same units. In the electrical circuit,  $1/\rho$  is the conductivity of the material in the circuit and determines what current density,  $i$ , will flow under the voltage gradient  $E/l$ . As shown by Eq. 8.5a the total flux is related to the mmf and the constants of the magnetic circuit just as Ohm's law relates the current to the voltage and resistance of a d-c electric circuit. For magnetic circuits it is more practical, partly because of the nonlinear nature of  $\mu$ , to give data in terms of flux density and ampere-turns per unit of length.

The analogy between magnetic and electrical circuits is not complete, and they differ in several respects. The permeability,  $\mu$ , varies considerably, whereas the electrical resistivity,  $\rho$ , is relatively constant for a conductor. There is also less difference between the permeability of the magnetic path and the permeability of the surrounding medium than there is for the resistivity of the conductor and the surrounding medium. This results in a less well-defined circuit for magnetic flux and leads to the phenomenon of *leakage flux*, which is vitally important

in electrical apparatus. Further, the cross-sectional area of magnetic circuits is comparatively large, and large errors can be made by assuming uniform flux distribution.

Using Eq. 8.5 and the law of continuity of flux (all lines of flux are closed loops), magnetic circuits in parallel or in series can be solved in exactly the same manner that d-c electrical circuits are worked out.

**8.6. Hysteresis Loop.** The hysteresis loop is a curve plotted between  $B$  and  $H$  for various values of  $H$  from a maximum value in the positive direction to a maximum value in the negative direction and back again. Fig. 8.4 shows a typical hysteresis loop.

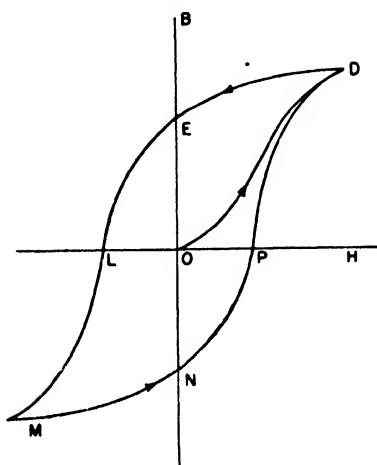


FIG. 8.4. Hysteresis loop for a ferromagnetic material. This could be determined experimentally from a toroid (Fig. 8.1b) by using a ferromagnetic core. Curve  $OD$  is the magnetization curve, length  $OE$  is the residual induction, and  $OL$  is the coercive force. The width of the loop (length  $LP$ ) is much exaggerated compared with materials used in a-c magnets.

Starting at zero with a coil wound around a toroid of unmagnetized iron, the magnetization curve follows curve  $OD$ . If the mmf is gradually reduced, the flux curve follows the line  $DE$ . As mmf is reversed, the flux falls to the point  $L$  and thence to  $M$ . As the current is increased, the flux traces out the path  $MNPD$ . The area within the closed loop is a measure of energy lost during the cycle. This energy is, in effect, a frictional loss and shows up as heat in the material. The distance  $OE$  is a measure of the residual flux left in the *closed* magnetic circuit when the current is zero. It is known as  $B_r$ , the *residual induction*.  $B_r$  describes circuits in which there are no air gaps, e.g., the iron toroid, and should not be confused with *remanence*, a more general term which refers to the magnetic induction remaining in the magnetic circuit (usually in the air gap when one is present) after the magnetizing force has been removed.

The distance  $OL$  is known as  $H_c$ , the *coercive force*, and is the value of the demagnetizing force required to bring the induction to zero when such a loop is being traced out.

If a ferromagnetic substance is subjected to an alternating mmf, the first hysteresis loops traced out do not necessarily fall upon each other. When successive loops retrace preceding ones, the material is said to be

in a *cyclically magnetized* condition. For electromagnet core materials, values of  $B_r$  and  $H_c$  are determined from a hysteresis loop taken when the material is cyclically magnetized. Permanent magnet values, however, are taken from the first hysteresis loop, since permanent magnets need be magnetized only once.

**8.7. Important Characteristics of Electromagnet Materials.** For ordinary industrial electromagnet materials, the magnetic qualities which are usually specified or evaluated are: (1) Saturation curve and intrinsic saturation, (2) hysteresis loss, (3) eddy current loss, (4) maximum permeability.

The order of importance to the user depends largely on the application. In addition there are many other qualities which must be considered, some of which are: (1) Cost; (2) mechanical properties such as strength, ductility, warping, and distortion; (3) manufacturing properties such as drawing, brazing, welding, and machining qualities, and effect on die life; (4) electrical resistivity, which is one of the factors determining eddy current loss; (5) thermal conductivity; (6) aging characteristics; (7) corrosion resistance; (8) initial permeability. Some of these qualities will now be discussed in a general way. More specific details will be found later under the particular magnetic materials treated.

**8.8. Saturation Curve.** Fig. 8.3 contains magnetization data on the most important ferromagnetic materials, and it provides a basis for dividing the materials roughly into three main groups. The first group includes those materials to the extreme left of the curve: nickel-iron alloy (Nicaloi), Permalloy, and Mu-metal. These give appreciable flux densities at very low magnetizing forces. The next group may be considered as including the materials between electrolytic iron on one side and steel or malleable iron castings on the other. In this group are the bulk of industrial magnetic materials. The third group is at the right-hand section of the curve and consists primarily of the permanent magnet materials.

The cobalt alloys have the highest intrinsic saturation values and are followed in decreasing order by electrolytic iron, Armco iron, cold-rolled steel, low silicon steel, high silicon steel, iron-nickel alloy, Permalloy, and Mu-metal.

**8.9. Core Loss.** The total core loss is the sum of the hysteresis and the eddy current losses. In practice, it is determined by the Epstein test, in which a sample of standard dimensions is operated with a standard flux density and frequency, and the power loss in the sample is measured.

**Hysteresis Loss.** The hysteresis loss is proportional to the area of the

hysteresis loop. Steinmetz developed the law:

$$W_h = \eta f B^x \quad [8.6]$$

where  $W_h$  = hysteresis loss,

$\eta$  = constant proportional to the area, material, heat treatment, etc.,

$x$  = 1.6 for some types of iron,

$B$  = maximum flux density attained,

$f$  = frequency.

On many present-day materials the exponent  $x$  is considerably greater than 1.6, being almost equal to 3 for some silicon steels. Ordinarily, hysteresis losses at various densities are taken from laboratory tests, since no value of  $\eta$  will fit the loss curve over a wide range of values of density, and misuse of the equation will usually bring about very large errors.

*Eddy Current Loss.* Whenever the flux in a magnetic material changes its value, voltages are induced which cause eddy currents to circulate in the material. The value of the eddy current loss depends on the resistivity and thickness of the material, the frequency, and the flux density as shown by the following equation:

$$W_e = \frac{Kf^2 B^2 t^2}{\rho} \quad [8.7]$$

where  $K = 1.645 \times 10^{-16}$ ,

$W_e$  = watts eddy current loss per cubic centimeter,

$t$  = lamination thickness in cm,

$B$  = maximum flux density in gausses,

$\rho$  = resistivity in ohm-cm.

In general, the eddy current losses given by this formula are lower than actual test values so that, as for the hysteresis loss, data are obtained from laboratory tests rather than from theoretical calculations.

It has been proved that the eddy current loss increases with increasing grain size up to the point where the grains become as thick as the laminations. This leads to higher-than-calculated losses for materials such as silicon steel, which have large grain size.

Despite theory, it has also been shown that eddy current losses are not directly proportional to the square of the lamination thickness but decrease less rapidly than the square law with decreasing thickness. There is a limit in lamination thickness below which it is not feasible to go because of the excessive space taken by the electrical insulation on the sheets. Since this insulation is of approximately the same thick-

ness, independent of sheet thickness, the percentage of nonuseful space increases as the lamination thickness decreases.

**8.10. Other Factors Affecting Core Loss.** There are several factors which tend to make core losses in electrical apparatus greater than those measured by the Epstein test. In fact, the Epstein test must be treated primarily as a standard to define purchasing specifications and material identification and cannot be used too literally for engineering design. Some of these factors which often make losses in apparatus considerably higher than Epstein tests would indicate are discussed below.

**Burrs.** As dies become worn, the burrs which they form on punched edges of lamination stock become larger and larger. These burrs are not always removed by de-burring operations, and they cut through sheet insulation forming contacts between laminations and allowing excessive eddy currents to flow. These are commonly referred to as inter-sheet eddy currents. Machining operations which are performed on stacked laminations, such as the grinding of induction motor stators, or broaching of solenoid faces, often smear the laminations together, forming good connections between sheets. Many schemes, such as treating the faces with acid or alkali, have been tried in an attempt to eat away the metal particles, but this attempted cure often causes other troubles, such as rusting. Burning off the burrs with a flame has also been attempted with varying success.

**Rivets and Bolts.** Laminations must be held together. A common method is to use rivets or bolts, but they tend to short out lamination insulation and very often form part of a closed loop which, under a-c operation, causes a serious loss of electrical energy.

**Pressure.** Mechanical strains set up in magnetic materials either from (a) cold working during rolling or punching or (b) distortion during final assembly operations affect magnetic properties in several ways. The hysteresis and eddy current losses as well as the magnetizing current are all increased. The increased hysteresis loss due to punching depends upon the material, its thickness, and the configuration of the grains. The loss may be as high as 300 per cent of the loss in the unpunched sheet. The strains produced by punching operations increase the loss primarily in the narrow section next to the punched edge. The per cent increase in hysteresis loss is much lower for high flux densities than for lower.

The effect of tension on silicon steel is to increase the permeability until high flux densities are reached. The effect of compression, however, is much more marked than that of tension and reduces the permeability considerably. Fig. 8.5 shows the effect of compression on the saturation curve of a 3 per cent silicon steel.

*Hysteresis Loss in Silicon Steel Scale.* The surface scale on iron and steel (usually an oxide) is partially magnetic and at high flux densities carries appreciable flux. The scale has a very high hysteresis coefficient so that as it begins to carry flux the total hysteresis loss increases rapidly. To lessen this type of loss, the oxide is removed by acid pickling and the laminae are then coated with an enamel having inherently low hysteresis loss.

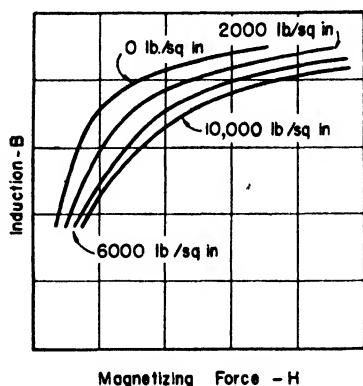


FIG. 8.5. Magnetization curves drawn to scale for a 3 per cent silicon sheet steel sample subjected to various values of compressive stress. The effect of tensile stress is not as pronounced.

determining this coefficient is to take data before and after holding the material at 100°C for 600 hr.

Aging is of importance in apparatus because it causes a deterioration in magnetic qualities with a consequent increase in magnetizing current and core loss. In devices such as magnets, contactors, or brakes, an increase in the hysteresis loop means essentially an increase in coercive force which may cause an armature to "stick" closed owing to remanence.

## ELECTROMAGNET MATERIALS

**8.11. Effect of Impurities and Alloying Elements.** The most common impurities in iron are carbon, oxygen, nitrogen, manganese, sulphur, and phosphorus. In general, impurities cause a decrease in permeability and an increase in hysteresis loss.

A very slight amount of carbon reduces the permeability tremendously, lowers the saturation point, and increases the area of the hysteresis loop, which causes an increase in coercive force and a decrease in

*Aging.* The normal or accelerated change in magnetic properties of a magnetic material under normal or specified conditions is called *aging*. When used in reference to core loss in an electromagnet material, this term implies an increase in loss. When used in reference to permeability or remanence (Sec. 8.6), a positive value of aging coefficient indicates a decrease in these quantities. In order to obtain the aging coefficient, a material is usually held at a slightly elevated temperature for a certain number of hours. An accepted laboratory method of determining this coefficient is to take data before and after holding the material at 100°C for 600 hr.

residual induction. The form in which carbon appears, that is, cementite or graphite, modifies its influence on magnetic properties.

Next to carbon, sulphur has the greatest detrimental effect. Even very small amounts are harmful.

Phosphorus and oxygen also lower the permeability and increase the hysteresis loss, and attempts are made to minimize their percentages.

Very small amounts of manganese are only slightly harmful. About 0.5 per cent manganese causes the same hysteresis loss as 0.03 per cent sulphur.

Copper is often added to steel to increase its corrosion resistance. In amounts up to 0.5 per cent it has little effect on magnetic properties.

Silicon is the most important nonmagnetic element with which iron is alloyed. The resistivity of iron is increased approximately 11 microhm-cm for each per cent increase in silicon. Since the resistivity of pure iron is about 10 microhm-cm, the addition of 1 per cent of silicon will double the resistivity, reducing the eddy current loss considerably. Silicon also improves the permeability at low inductions, decreases the intrinsic saturation, and decreases the hysteresis loss. The magnetic improvement is due principally to the elimination of the harmful effects of oxygen and to the reduction of carbon to its less harmful graphitic form. Silicon also reduces aging to a negligible figure. Aluminum is more powerful than silicon as a deoxidizer and has about the same effect on the mechanical properties of iron.

The resultant magnetic properties are not quite as good, so that, as yet, aluminum is seldom used as an alloying element for magnetic irons.

**8.12. Effect of Direction of the Grain.** Electrical strip steels have been developed which have considerably different properties depending on the direction of the flux relative to the direction of rolling. Strip steel, which is rolled in a continuous mill, must not be confused with sheet steel, which, during finishing, is alternately rolled along, then across the sheet. Fig. 8.6 shows the saturation curves on a strip steel

"with grain," at "cross grain," and at 45 degrees to the grain. Cross-grain pieces also have higher hysteresis loss and it is for this reason that the Epstein test specifies that one-half the samples be taken with the

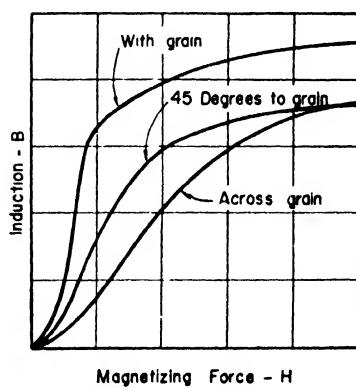


FIG. 8.6. Magnetization curves drawn to scale for 3 per cent silicon cold rolled strip steel, showing the effect of direction of rolling.

grain and one-half across the grain. The magnetic cores for some transformers are wound from strip so that the flux direction is aligned with the grains.

**8.13. Effect of Temperature.** For fairly small temperature increases, the magnetic properties of iron and iron-silicon alloys are only slightly affected. In general the permeability is improved and the hysteresis and eddy current losses are decreased. The core losses continue to decrease as the temperature approaches the *Curie point*<sup>1</sup> (the critical temperature at which steel becomes nonmagnetic). For medium and high inductions, the permeability decreases with increasing temperature until it reaches unity at the critical point.

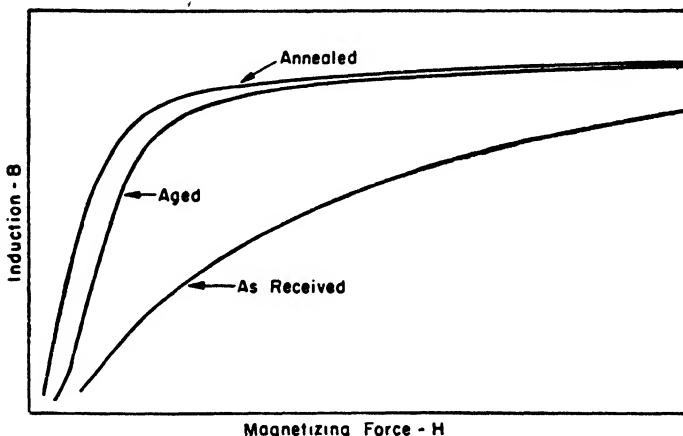


FIG. 8.7. Magnetization curves for Armco ingot iron, as received, after hydrogen anneal, and after two weeks of aging at 100 C. Note that the intrinsic saturation is the same in each case.

**8.14. Heat Treatment.** The magnetic properties of all magnetic materials are largely dependent on the type of heat treatment they receive. Annealing is usually accomplished in an inert or reducing atmosphere and tends to remove the carbon and to relieve internal elastic strains, thus reducing the area of the hysteresis loop and altering the saturation curve (see Fig. 8.7). Other strains may remain, however. Impurities disrupt the orderly arrangement of the atoms and set up strains, so freedom from dissolved impurities is very important. There are also strains set up by the magnetization, the change in length being called *magnetostriction*.

<sup>1</sup> When a wide variation of permeability with temperature is desired, such as in overload indicators or thermal devices, "Curie alloys" are used. A typical one has a composition of 30 per cent nickel, 70 per cent iron, and doubles its induction when cooled from 41 to 23 C.

**8.15. Demagnetizing.** It is frequently necessary to demagnetize iron. A common application occurs with the use of magnetic chucks where it is necessary to demagnetize the chuck and perhaps a large solid section of material in order to remove the work. Demagnetization is accomplished by applying a field which produces a flux as high as the remanence flux existing in the body or higher. This flux is then reversed to a negative value which is only slightly less than the previous positive value. The current is then successively increased and decreased, the maximum amplitude being reduced on each reversal until a small value

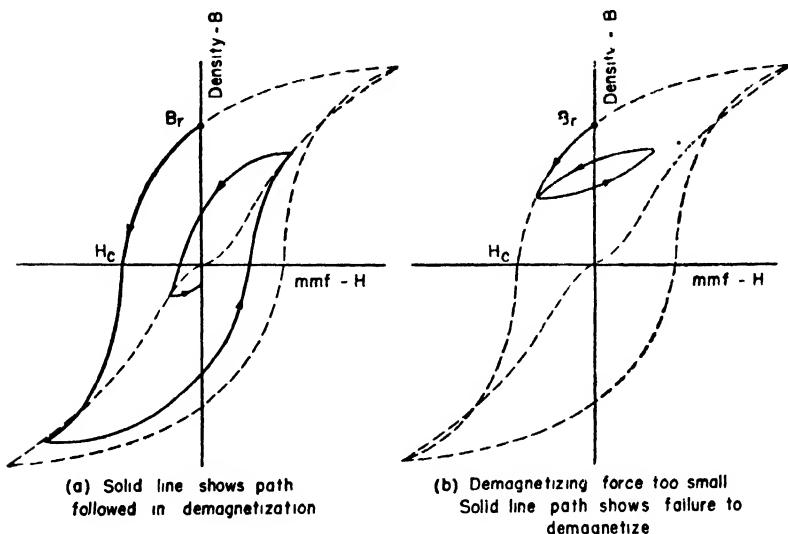


FIG. 8.8. Paths followed in (a) successful and (b) unsuccessful attempts to demagnetize a metal. For a successful operation, the demagnetizing mmf at each half-cycle must be greater than the coercive force, but less than the mmf at the previous half-cycle.

of current, perhaps 10 per cent of the original value, is attained. The efficiency of demagnetizing depends not so much on the total time consumed as on the rate at which the demagnetizing current is changed. For solid materials it is often impossible to get good demagnetizing results if a frequency as high as 60 cycles is used because the shielding effect of eddy currents prevents the penetration of the flux. Demagnetizing cannot always be accomplished by applying a low value of current. Fig. 8.8a shows the path traced out during a demagnetizing cycle such as the one described. Fig. 8.8b shows what may occur if only a small mmf is applied to a body having high remanence flux.

A *minor hysteresis* loop is obtained which still leaves the material magnetized.

**8.16. Silicon Steels.** The silicon steels form the most important group of magnetic materials for alternating current applications, such as transformers, generators, motors, and relays. The term "electrical sheets" is a trade name for iron and steel sheets used in the manufacture of punchings for laminated magnetic circuits and usually refers to a silicon sheet steel. The manufacture of lamination steels for electrical purposes has become very standardized. Most manufacturers make about five standard grades, each of which meets certain *guaranteed core losses*. Their grade names, shown in Table 8.1 below, are dependent primarily on the silicon content. In general, the higher silicon magnet steels have lower losses and lower strength. Because of their widespread use and importance, these grades will be discussed briefly.

TABLE 8.1

	Approx. silicon %	Resistivity, microhm-cm	Per cent of sheet losses	
			Eddy current	Hysteresis
Armature	0.5	19	55	45
Electrical	1.0	25	53	47
Motor	2.5	43	52	48
Dynamo	3.5	54	41	59
Transformer	4.5	65	35	65

**Armature.** This is the lowest cost mill-annealed steel that can be bought with a core loss guarantee. Its surface condition may not be uniform. It is used in d-c machines or in small apparatus for short duty. It has good machining qualities and can be deep drawn if normalized.

**Electrical.** This is the lowest grade mill-annealed steel with reliable core loss and mechanical properties. During rolling considerable care is taken to obtain a smooth surface free from loose and detachable scale. Its most important applications are in relays, and fractional horsepower and small railway motors, where its higher saturation limit makes it preferable to the higher silicon grades.

**Motor.** This grade is used for general purpose applications where low losses and fairly high magnetizing currents are required. It is the highest grade of silicon steel that has reliable mechanical properties. It is used in fractional horsepower motors, induction motors, synchronous and d-c machines and for general purpose a-c control apparatus.

*Dynamo.* This grade is used where high efficiency and low losses are required, but is employed in rotating apparatus only where low stresses are involved because it is somewhat brittle. It is used in high efficiency apparatus and lower grade transformers.

*Transformer.* There are several grades of transformer steel made to have low losses without particular regard to mechanical properties. Because of their high silicon content, these steels are so brittle as to be unsuitable for rotating apparatus.

**8.17. Other Irons and Steels.** *Ingot Iron.* This iron is the purest form of iron obtained commercially. The American Rolling Mill Company ingot iron known as Armco iron is guaranteed to be 99.85 per cent pure. Its intrinsic saturation is very high, as shown in Fig. 8.3. It can be worked mechanically, such as by rolling, but only in certain temperature ranges (see Fig. 4.10). If worked outside these limits, it becomes brittle and cracks. This iron also has poor aging qualities. It is used wherever advantage can be taken of its very good magnetization curve and high saturation. It is commonly used in pole faces, in frames of d-c machines, and for time delay relays in control apparatus. Its resistance is low, 10.7 microhm-cm.

*Wrought Iron.* The better grades of wrought iron are often known as Norway iron or Swedish iron. They are widely used in relays after being annealed to reduce hysteresis and to prevent aging.

*Mild or Low Carbon Steel.* Open hearth steel of low carbon content has fairly good magnetic properties and is used quite extensively as a magnetic material. It is even made into electrical sheets of ordinary grade but is, of course, inferior to the silicon steel in core losses and aging, though it is superior in magnetization (more flux for the same mmf) and is lower in cost. This steel is used extensively for d-c solenoids, magnetic brakes, and clutches. The frames of d-c machines which were formerly made of cast iron are now largely made of rolled and welded soft steel plates.

*Cast Iron.* Cast iron has a very poor magnetization curve but is used in magnetic circuits principally because of the advantages it offers in manufacturing.

*Cast Steel.* Cast steel has a good magnetization curve and is used on d-c machines where high mechanical strength is required. All the above irons and steels require an annealing treatment in order to obtain best magnetic quality.

**8.18. Ferromagnetic Alloys.** *Nickel-Iron Alloys.* Alloys of nickel and iron have a wide range of magnetic properties. The three curves on the extreme left in Fig. 8.3 show the particular properties which some of these alloys possess. In general, they have high per-

meability and low hysteresis loss at low magnetizing forces. Most of them are very sensitive to mechanical strain and usually require special heat treatment after all mechanical operations have been completed.

The most common materials in this class are Permalloy and Mu-metal. Permalloy is the name applied to a number of nickel-iron alloys with high nickel contents. They are used for the continuous loading of submarine cables and in loading coils for land lines. Mu-metal (74 Ni, 4 Cu, 1.4 Cr, bal. Fe) is similar in properties to the Permalloy which has 78 per cent nickel. However, it has a higher initial permeability and lower coercive force than Permalloy. An alloy of about 47 per cent nickel has been developed as a high permeability alloy for radio and other applications where magnetizing forces are low. It is extensively used in current transformers, reactors, relays, and instruments. With special melting and annealing treatment, it is known as Hypernik.

*Iron-Cobalt Alloys.* The addition of cobalt up to 36 per cent raises the saturation point of iron (see Fig. 8.3). These alloys are therefore used wherever very high densities are required such as in the pole pieces of electromagnets. This alloy is quite brittle when cold. The 50 per cent cobalt-iron alloy is known as Permendur.

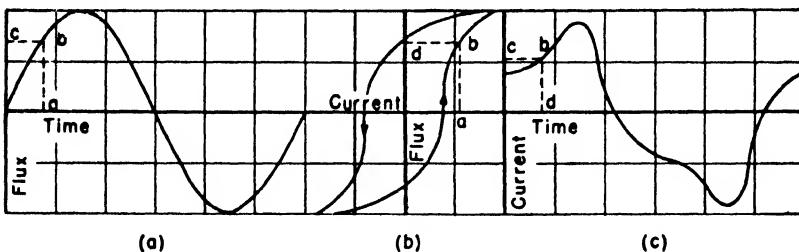


FIG. 8.9. The harmonic flux wave of a transformer core is shown in (a), and the hysteresis loop in (b). By combining values scaled from (a) and (b) as shown, the exciting current wave (c) can be drawn.

**8.19. Effect of Iron in A-C Circuits. Saturation Curve.** The saturation curve given for 60 cycle alternating current is somewhat lower than the direct current curve which would be obtained. This is due to the shielding effect of the induced eddy currents.

*Third Harmonic.* If a sine wave of voltage is applied to a transformer, the resulting current flow is not usually a sine wave but is quite unsymmetrical. Fig. 8.9a shows a sinusoidal flux density wave corresponding to normal sine-wave excitation. The number of ampere-turns, and therefore the current which must flow at any instant to produce the required flux, is easily determined by reading the corresponding values

*cb* and *bd* from Fig. 8.9a and 8.9b respectively. The only precaution to be observed is that the ascending part of the loop should be read for the ascending part of the flux-density wave and the descending part of the loop for the descending part of the flux-density wave.

The current wave so drawn (Fig. 8.9c) includes the hysteresis-loss component of current as well as the wattless component of the exciting current.

The analysis of the magnetizing current wave shows that it contains a third harmonic which is as much as 50 per cent of the fundamental for a large (1000 kva) high-core-density transformer and is about 20 per cent for a 50 kva unit. Higher multiple harmonics are also present.

*Inrush Current.* The residual flux which remains in a magnetic circuit can cause very high currents to flow when the transformer is switched on the line. In a good magnetic circuit such as may be found in a wound core transformer, this residual may be as much as 70 per cent of the maximum flux density attained throughout a cycle. This residual flux can cause transients which are 300 to 400 times normal magnetizing current.

## PERMANENT MAGNETS AND MATERIALS

By S. C. HOARE and R. E. MOORE

A permanent magnet is a source of *magnetic potential* and possesses internal reluctance (magnetic resistance), both of which vary in magnitude with the magnetic load imposed by an air gap, or other demagnetizing influence. When the load is progressively increased to higher values and then reduced (air gap lengthened, then shortened), the potential and reluctance are only partly recoverable. In other words, the conditions within the magnet depend upon the history of loading. A magnet delivers its maximum magnetic energy when the reluctance of the load equals that of the magnet.

**8.20. Hysteresis Loops.** The hysteresis loop of Fig. 8.10 gives the magnetic properties of a closed ring of Alnico for various stages of cyclic magnetization. Values of the magnetizing force,  $H$ , and the induction,  $B$ , are in the "per unit" form, that is,  $H$ -per centimeter of length and  $B$ -per square centimeter of cross-section.

The virgin curve shows the initial magnetization, beginning with the completely unmagnetized alloy. When the magnetizing force reaches the value of about  $H_p = 2000$  oersteds, the alloy is fully saturated. Further increase of  $H$  will, of course, result in an increase of induction  $B$ , in accordance with the air line mentioned earlier. The intrinsic saturation of the alloy, however, remains fixed and is  $B_s = B_p - H_p$ .

Fig. 8.10 indicates that a magnet of Alnico II requires a magnetizing force of at least  $H_p = 2000$  oersteds for each centimeter of its length to reach saturation. This is equivalent to 4040 ampere-turns per inch. (See Eq. 8.2.)

If, after the virgin curve has been established at  $H_p = 2000$ , the magnetizing force is then decreased to zero, the induction falls, not to zero, but to  $B_r = 7300$  gauss, the residual induction. It is necessary to apply a reversed magnetizing force (demagnetizing force) of  $H_c = 560$  oersteds to reduce the induction to zero.

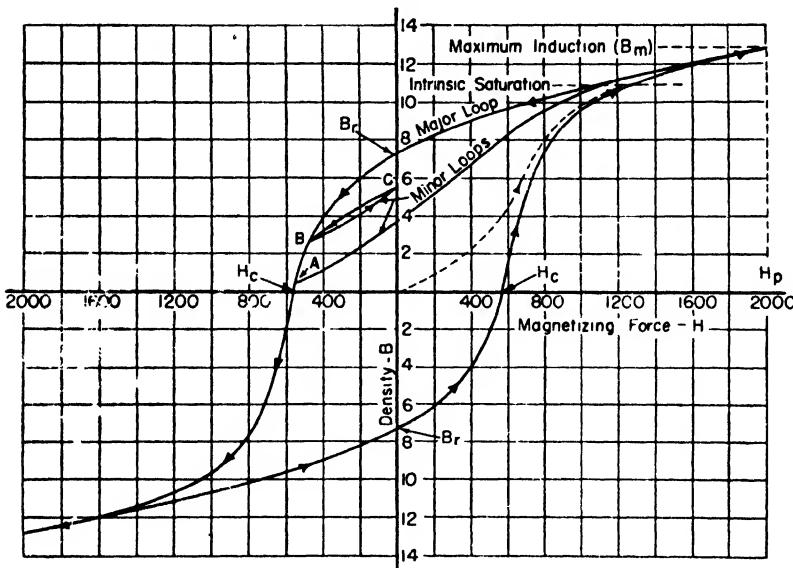


FIG. 8.10. Hysteresis loop of Alnico II permanent magnet alloy.

**Minor Loops.** Consider now that at point *A*, say, on the upper branch of the loop of Fig. 8.10, the cyclic variation of  $H$  is interrupted and  $H$  is now caused to increase in the positive direction. Induction in the alloy will now return along a new curve, which is part of the *minor loop*. Minor loops can be taken starting at any point on the curve and can be of any length less than that of the major loop; the permanent magnet designer is concerned chiefly with the short minor loop which occupies the demagnetizing quadrant, for example, loop *B-C*.

**8.21. Demagnetizing and External Energy Curves.** The most useful portion of the major hysteresis loop is the *demagnetizing curve* (that section in the second quadrant),  $B_r$ , to  $H_c$ . This is now redrawn in enlarged form in Fig. 8.11. To this is added a curve of *external energy*

which is derived from the product of  $B$  and  $H$  for points along the demagnetizing curve. This energy curve is an index of the magnetic energy which the magnet can deliver to the external circuit, per unit volume of the alloy magnet, for various values of  $B$  and  $H$ . Thus  $BH_{\max}$  is an important criterion in comparing magnet materials. Strictly speaking, the magnetic energy is  $BH/8\pi$  ergs per unit volume of alloy, but for simplicity the  $8\pi$  is dropped and relative values are expressed as the simple  $BH$  product.

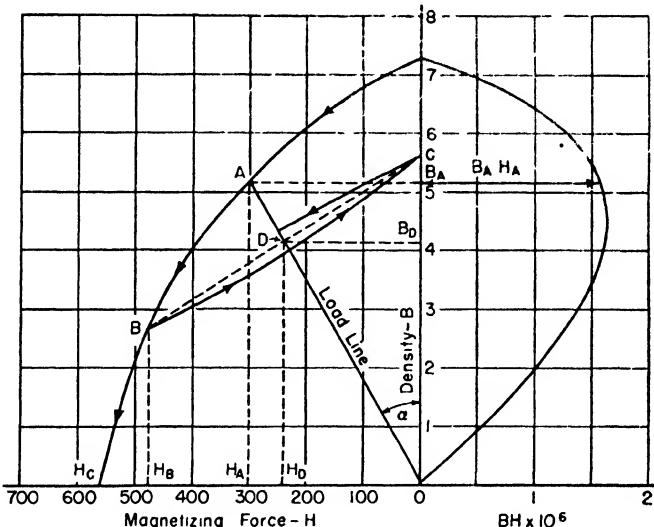


FIG. 8.11. Demagnetizing and external energy curves for Alnico II. The demagnetization curve consists simply of the second quadrant section of Fig. 8.10, and the external energy curve is calculated by multiplying  $B \times H$  for each point along the demagnetization curve.

**8.22. Electrical Analogy.** The demagnetization curve (Fig. 8.11) may be compared to the volt-ampere characteristic of a battery having an internal resistance and connected to an external load resistor. The coercive force,  $H_c$ , is analogous to the open circuit voltage of the battery, and  $B_s$  is analogous to the short circuit current,  $I_{sc}$ . To find the current which will flow through any load resistor,  $R$ , a line  $E = IR$  is drawn making an angle  $\alpha = \tan^{-1} R$  with the current axis. The intersection of this straight line with the curve gives the resulting current. The power delivered to the external load is the product of voltage and current at this point.

Similarly, in permanent magnet design, the load line  $OA$  is drawn so that  $\tan \alpha$  is equal to the reluctance of the air gap in terms of its

dimensions. The operating point of the circuit is at  $A$ , and the product of the flux,  $B_A$ , and the magnetizing force,  $H_A$ , is proportional to the energy stored in the air gap per unit volume of magnet material.

In using this analogy, it must be remembered that the operating point  $A$  does not always stay on the demagnetization curve, but may move down to a position on a minor loop. In other words, the history of loading determines the operating point, as was explained above, and the external energy at that point (proportional to  $B_D H_D$ ) is considerably less than at point  $A$ .

Methods of applying these magnetic characteristics to problems of analysis and design are straightforward. Simple and symmetrical magnetic circuits can be calculated to an accuracy within a very few per cent. Complicated arrangements do not permit precise treatment of leakage reluctance, and either an estimate or a graphical solution may be used, the accuracy of the method depending upon the need.

**8.23. Magnetic Circuit Containing an Air Gap.** The point  $A$  on the curve of Fig. 8.11 is the initial *knockdown* of the magnet due to the demagnetizing effect of the air gap. If now the magnet is demagnetized further either by temporary increase of the air gap length or by temporary application of a d-c field, the induction falls, say to point  $B$  (corresponding to  $H_B$ ). Upon removal of the temporary demagnetizing force, the induction rises, not to point  $A$  but to point  $D$  on the load line. Actually, the induction will fall slightly lower than  $D$  on the load line, but because of the small "spread" of minor loops in this quadrant, for practical purposes, the induction may be considered as falling back along the axis of the minor loop.

The minor loop illustrates the demagnetizing protection given by magnetic knockdown; by reducing the magnet strength, the stability of the magnet is increased. Taking the initial condition represented by point  $A$ , any temporary increase of demagnetizing force beyond  $H_A$  results in a permanent decrease in induction. A temporary knockdown to  $H_B$  gives the magnet a "reserve magnetizing force," not of  $H_B - H_A$  but of  $H_B - H_D$ . The permanent knockdown in induction to obtain this protection is  $B_A - B_D$ . After this permanent knockdown, there will be no permanent changes in induction until a total demagnetizing force in excess of  $H_B$  is applied. A force greater than  $H_B$  will immediately initiate a new minor loop lower in the quadrant.

If, after knockdown, the magnet is slightly magnetized so that point  $D$  is at the top of the minor loop, instead of the bottom, there will be less knockdown but practically the same reserve of  $H_B - H_D$ .

**8.24. Permanent Magnet Materials.** Hardened unalloyed carbon steel was the best permanent magnet material known until early in the

present century, when it was found that stronger and more stable magnets could be made of tungsten or of chromium steel. In 1920 Honda announced the development of cobalt magnet steel, which had three times the coercive force of tungsten or chromium steel and about the same residual induction. Like all the preceding permanent materials, except lodestone, this material was a carbon steel which had to be quenched in oil or water from a high temperature in order to develop its permanent magnet qualities.

About 10 yr ago the first of the age hardening permanent magnet alloys was produced. These materials differ from the carbon steel in that they contain no carbon except as an undesirable impurity and in that their final heat treatment is usually a slow cooling at a controlled rate or a prolonged heating at a temperature not higher than a dull red heat. Quenching is sometimes used as a preliminary treatment to bring the constituents into a solid solution in the alloy. In this condition, the alloy is most workable but it has very poor magnetic properties. The low temperature heating or precipitation treatment increases the hardness of the alloy in addition to developing its permanent magnet qualities. Alnico belongs in this class of materials and its precipitation treatment may consist in a controlled cooling from a high temperature rather than a prolonged heating.

Oxide magnets belong in a third class of permanent magnet materials. They include lodestone and sintered oxide. One of the latter materials, a mixture of iron and cobalt oxides, is pressed and fired at a high temperature so that the particles unite and diffuse into each other without actually melting. It is subsequently heat treated in a magnetic field. This material is used because of its light weight and high coercive force, which make it suitable for the moving elements of electrical instruments.

In terms of maximum external energy (proportional to  $BH_{\max}$ ), cobalt steel is three times as good as tungsten steel and Alnico V is five times as good as cobalt steel. By the same criterion, tungsten steel is about twice as good as carbon steel.

**8.25. Theory of Permanent Magnet Materials.** The theory of permanent magnet materials is far from complete. The basic requirements are that the alloy shall contain one or more ferromagnetic materials and one or more nonmagnetic materials. The function of the nonmagnetic materials is to distort or strain the crystal lattice of the ferromagnetic material, since a strained lattice appears to be essential for a high coercive force. No success has been achieved in predicting the magnetic properties of alloys from theoretical considerations. Since the best permanent magnet alloys contain five or more metals, the

possible number of combinations of ingredients and heat treatments is enormous. Eventually, an increase in theoretical knowledge should simplify the present trial-and-error methods of development.

**8.26. Aging.** Aging (of a permanent magnet) is the process of normal or accelerated change, under continued normal or specified artificial conditions, in the strength of the magnetic field maintained by a permanent magnet. The change in field strength due to aging is usually expressed in per cent.

Aging may be of two types, metallurgical or magnetic, and each type may occur either singly or in combination with the other.

*Metallurgical aging* is a result of a change in the metallurgical condition of the magnet steel, which changes its ability to maintain itself in a magnetized condition. This change may begin immediately after the steel is hardened and, at room temperature, may continue at a diminishing rate for a long period of time. High temperatures usually accelerate these metallurgical changes. Hence most permanent magnet materials are stabilized by baking for about 24 hr at a temperature between 100 and 200 C. The change may also be accelerated in some materials by decreasing the temperature, by cyclic temperature changes, and possibly to some extent by mechanical vibration. Magnets which have been metallurgically aged cannot be restored to their original strength by remagnetization.

*Magnetic aging* is the result of some external influence which causes a change in the strength of the magnetic field being maintained by the magnet, but does not alter the metallurgical condition of the magnet steel as far as its magnetic properties are concerned. Magnets which have suffered only magnetic aging may be restored to their original strength by remagnetization.

The four main causes of magnetic aging are as follows:

- (1) Presence of strong external magnetic fields;
- (2) mechanical vibration (when the aging does not result from metallurgical changes which may be induced by the vibration);
- (3) changes in the external magnetic circuit, such as increasing the air gap length, removing the "keeper," or sliding a piece of soft iron over the magnet;
- (4) temperature conditions (when the aging does not result from metallurgical changes which may be induced by these temperature conditions).

After the metallurgical stabilization has been completed and a permanent magnet is magnetized, heating and cooling within the temperature range 100 to -40 C may cause a demagnetization of 0.5 per cent or less. Subsequent temperature cycles within this range will have little or no permanent effect on the magnet strength although there is a cyclic change in the strength of all permanent magnets due to temperature.

The strength is always slightly greater at low temperatures. The coercive force of sintered oxide decreases rapidly with increasing temperature so that it must not be used in applications which combine

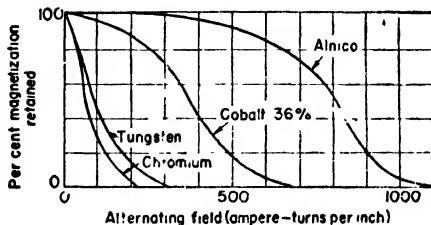


FIG. 8.12. Relative magnetic retention in an alternating magnetic field.

temperatures above 70 to 80 C with strong demagnetizing fields. Temperature tests are always made in connection with new applications of the recently developed magnetic materials in order to study their performance under various thermal and magnetic field conditions.

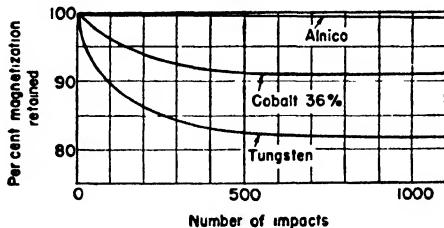


FIG. 8.13. Relative magnetic retention after impact.

Figures 8.12, 8.13, and 8.14 show the relative effects of stray fields, impact, and heating upon various permanent magnet materials.

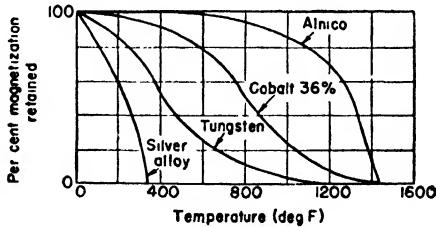


FIG. 8.14. Relative magnetic retention after heating.

**8.27. Alnico.** Alnico represents the most widely used group of the new alloys. It has high values of  $B_r$  and  $H_c$ , as shown in Fig. 8.15. The principal constituents are aluminum, nickel, cobalt, and iron, in the proportions shown in Table 8.2.

*Fabrication Methods.* Compared with the older magnet materials, Alnico is more difficult to form. Chromium or tungsten steels may be hot pressed and formed, then drilled or machined when cold. After final forming, they are heat treated to develop the desired magnetic qualities.

These methods cannot be used to fabricate magnets from Alnico. The Alnicos are a group of hard, brittle alloys which can be produced in only two ways: by sintering or by casting and grinding.

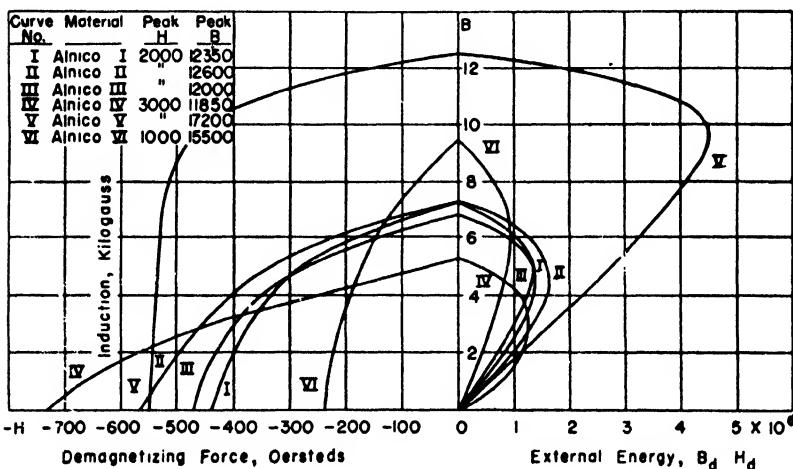


FIG. 8.15. Demagnetization and external energy curves for some Alnico alloys. This type is at present the most widely used permanent magnet material.

The sintering process is ideal for small magnets of certain designs but has definite limitations above a certain size. The process consists in blending the alloying elements in powder form by milling, pressing the powder mixture into a mold under high pressure, and firing the pressed parts at a high temperature, usually in hydrogen, until diffusion of the components produces a homogeneous alloy. The magnetic properties of properly made sintered material are equivalent to cast material of the same composition. An advantage of the process is that the pressed parts, before firing, are strong enough to allow drilling and machining operations to be performed before final firing. Reasonably good dimensions can be held, and for small high production parts, this process has real advantages.

Most Alnico magnets produced, however, are made by casting and grinding. The magnet must, of course, be designed for casting, and either a baked sand, green sand, or a permanent mold (in some cases)

TABLE 8.2. PROPERTIES OF SOME COMMON PERMANENT MAGNET MATERIALS

Mat. No.	Material	Typical composition	Coercive force	Residual induction $B_r$	$B \times H$ max.	Mechanical properties	Commercial methods of fabrication
1	Tungsten magnet steel	5 W, 1 C, bal. Fe	70	10,300	320,000	Hard, strong	Hot forge, punch, machine
2	Chromium magnet steel	3.5 Cr, 1 C, bal. Fe	65	9,000	295,000	Hard, strong	Hot forge, punch, cast, machine
3	10 Co magnet steel	2.44 W, 10 Co, 1.0 C, 1.4 Cr, bal. Fe	100	9,000	.....	Hard, strong	Hot forge, punch, cast, machine
4	36 Co magnet steel <sup>1</sup>	36 Co, 3.5 Cr, 3 W, 1 C, bal. Fe	210	9,000	930,000	Hard, strong	Hot forge, punch, cast, machine
5	Comol magnet alloy	12 Co, 17 Mo, bal. Fe	245	10,300	1,100,000	Hard, strong	Hot forge, punch, cast, machine
6	Alnico I	12 Al, 20 Ni, 5 Co, bal. Fe	400	7,100	1,330,000	Hard, brittle	Cast, sinter, grind
7	Alnico II	10 Al, 17 Ni, 12.5 Co, 6 Cu, Bal. Fe	540	7,200	1,650,000	Hard, brittle	Cast, sinter, grind
8	Alnico III	12 Al, 25 Ni, bal. Fe	400	7,100	1,330,000	Hard, brittle	Cast, sinter, grind
9	Alnico IV	12 Al, 28 Ni, 5 Co, bal. Fe	700	5,200	1,250,000	Hard, brittle	Cast, sinter, grind
10	Alnico V	8 Al, 14 Ni, 24 Co, 3 Cu, bal. Fe	550	12,500	4,500,000	Hard, brittle	Cast, grind
11	Fe-Ni-Cu alloy <sup>1</sup>	20 Fe, 20 Ni, 60 Cu	450	5,300	1,070,000	Ductile, malleable	Cold roll, machine, punch
12	Co-Ni-Cu alloy	41 Co, 24 Ni, 35 Cu	440	5,300	993,000	Ductile, malleable	Cold roll, machine, punch
13	Ni-Ti-Co-Fe <sup>2</sup>	16 Ni, 11 Ti, 28 Co, bal. Fe	830	7,500	Not given	Hard, brittle	Cast, sinter, grind
14	Sintered oxide	30.1 Fe <sub>2</sub> O <sub>3</sub> , 43.6 Fe <sub>3</sub> O <sub>4</sub> , 26.3 Co <sub>3</sub> O <sub>5</sub>	860	2,100	770,000	Soft, brittle	Sinter, grind, machine

<sup>1</sup> Fe-Ni-Cu alloy must be cold worked to develop magnetic properties.<sup>2</sup> U. S. patent 2,105,653 Honda. U. S. patent 2,264,038 Howe.

may be employed. The material cannot be readily machined or drilled even with cemented carbide tools, and such operations should be avoided in the design. Inserts of material, such as cold rolled steel, may be cast in and drilled or machined out afterward.

The casting technique is very important and must be well worked out, as the magnet goes practically from the molten state to its final form in a few seconds. Not only must a good casting be obtained mechanically, but the magnetic properties as well must be considered.

**8.28. Conclusion.** The various properties of ferromagnetic materials used in electromagnets and permanent magnets have been discussed, together with the effects of operating and processing conditions on these properties. The design of magnetic equipment must be based upon calculation or estimation of a number of these properties and conditions. Laboratory tests are helpful but consideration must also be given to the manufacturing processes to be used, the degree of control under which these processes are operating, and the effects of variations in the processes upon both the properties and the magnetic circuit.

### REVIEW QUESTIONS

1. How do diamagnetic, paramagnetic, and ferromagnetic materials react when exposed to a magnetic field?
2. (a) In English units, magnetizing force is expressed in ampere-turns per inch, and flux density in lines per square inch. What are the metric units for these quantities? (b) Write the equation which defines permeability. Are the units of the equation English, metric, or can either be used?
3. Sketch a magnetization curve and indicate an air line, the intrinsic flux, and the point of saturation.
4. Sketch a hysteresis loop, showing  $B_r$  and  $H_c$ . What is the significance of these quantities?
5. Laminations are usually stress-relief annealed after punching. What benefit does the relief of stress accomplish?
6. Core losses in silicon magnet steels decrease with increasing silicon content. Why should the low silicon steels be used at all?
7. Sketch hysteresis loops for (a) a transformer core material, (b) a permanent magnet material, and explain why each of them is adapted to its use.
8. Sketch a demagnetization curve and from it construct the external energy curve for that material.
9. In general, what is the purpose of heat treating a permanent magnet?

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## CHAPTER IX

### ELECTRICAL PROPERTIES OF MATERIALS

By R. E. COLEMAN, JR.

The successful operation of electrical apparatus frequently depends as much on the electrical properties of the materials selected as it does on their mechanical strength. The various electrical properties of materials are illustrated in this chapter by considering the properties and applications of electrical conductors and insulators.

There is no sharp dividing line between conductors and insulators. For practical purposes, however, conducting materials are selected to carry current in an electrical circuit and insulating materials are chosen to restrict the current to the desired path.

#### CONDUCTORS

**9.1. Resistance and Resistivity.** Most conductors are metal, but there is a wide range in their losses when they are carrying current (as much as 60 to 1, copper to Nichrome). They are usually thought of as either good conductors, such as silver, copper, and aluminum, or poor conductors (resistors), such as iron, alloys of nickel, iron, copper, and chromium, and carbon products.

No conductors are perfect. They cannot carry electric currents without losses. The power lost during the flow of current is proportional to the square of the current. The coefficient of proportionality is called the resistance and is denoted by  $R$ , as in Eq. 9.1.

$$W = I^2R \quad [9.1]$$

in which  $W$  = average rate at which electrical energy flowing through the conductor is converted into heat, in watts,

$I$  = current flowing in the conductor, in amperes,

$R$  = resistance of the conductor, in ohms.

The total resistance,  $R$ , of a conductor depends on its length, cross-sectional area, and volume resistivity, which is a property of the conducting material. The relation between these quantities is expressed by Eq. 9.2.

$$R = \rho l/A \quad [9.2]$$

TABLE 9.1. RESISTIVITIES OF MATERIALS

Material	Composition	Resistivity at 68°F		Cond. %	Temp. coeff. of resistance <sup>2</sup> °F <sup>-1</sup>
		10 <sup>-6</sup> ohm-in. <sup>1</sup>	oh.ms/cm <sup>2</sup>		
Silver		0.64	9.77	106	0.0021
Copper		0.68	10.37	100	0.0022
Gold		0.96	14.00	71	0.0019
Aluminum		1.12	17.01	61	0.0022
Magnesium		1.81	27.6	37.5	0.0044
Tungsten		2.17	33.1	31	0.0026
Zinc		2.26	34.5	30	0.0021
Cartridge brass	70 Cu, 30 Zn	2.47	37.6	27.5	0.0011
Zamak No. 3	95.9 Zn, 4 Al, 0.1 Cu	2.52	38.4	27	.
Nickel		3.08	47	22	0.0030
Phosphor bronze	95 Cu, 5 Sn	3.70	56.5	18	0.0022
Iron		3.93	58.8	17.5	0.0036
Platinum		3.93	58.8	17.5	0.0017
Tin		4.53	69	15	0.0023
Mild steel	99.75 Fe, 0.25 C	4.72	72	14.5	0.0024
Aluminum bronze	90 Cu, 10 Al	5.0	77	13.5	.
Magnesium alloy	89.9 Mg, 10 Al, 0.1 Mn	5.1-6.7	80-100	10-13	.
Lead		8.6	132	7.8	0.0021
Silicon bronze	96 Cu, 3 Si, 1 Mn	10.2	155	6.7	..
Monel	65-70 Ni, 26-30 Cu, 3 Fe, 1.5 Mn	17.6	268	3.9	0.0011
K-Monel	Monel with 3.75 Al	27.5	420	2.5	..
Stainless steel	18 Cr, 8 Ni, 0.10 C, balance Fe	33.1	500	2.0	..
Mercury		37.7	575	1.8	0.00049
Nichrome IV	80 Ni, 20 Cr	42.7	650	1.6	0.000072
Nichrome	60 Ni, 15 Cr, 25 Fe	44.3	675	1.5	0.000095
Graphite	(Crystalline)	315	4,800	0.2	..
Carbon	(Amorphous)	1380	21,000	0.05	..

<sup>1</sup> Multiply resistivity in ohm-in. by 2.54 to obtain resistivity in ohm-cm.<sup>2</sup> Multiply coefficient in °F<sup>-1</sup> by 1.80 to obtain coefficient in °C<sup>-1</sup>.

in which

Symbol	Units
$R$ = resistance of the conductor	ohms or ohms
$\rho$ = volume resistivity of the conducting material	ohm-in. or ohms/cm <sup>1</sup>
$l$ = length of the conductor	in. or ft
$A$ = cross-sectional area of the conductor	sq in. or cir mils

The volume resistivities of the common conducting materials, both in ohm-inches and ohms per cir mil foot, at 68 F (20 C) are given in Table 9.1. The materials are listed in the order of their conductivity, which is the reciprocal of resistivity. The conductivity of each material is also expressed as a percentage of the conductivity of copper.

The volume resistivity for most materials changes with temperature. The resistivity at 68 F is generally used, however, to calculate the resistance of conductors. The calculated resistance can then be corrected for other temperatures by using the temperature coefficient of resistance at 68 F, which is denoted by  $a$  in Eq. 9.3.

$$R_t = R[1 + a(t - 68)] \quad [9.3]$$

in which  $R_t$  = resistance of the conductor at temperature  $t$ , in ohms,

$R$  = resistance of the conductor at 68 F, in ohms,

$a$  = temperature coefficient of resistance at 68 F,  $1/^\circ\text{F}$ .

*Example.* A short example will illustrate the importance of resistance and resistivity. Consider a 5000 watt annealing furnace heater located 250 ft away from a 120 volt d-c source of electrical power (see Fig. 9.1). Tests show that the heater elements must be operated at 1800 F for this particular application.

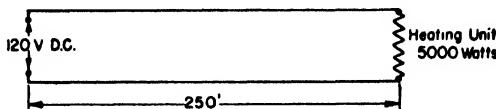


FIG. 9.1. Heating unit circuit.

<sup>1</sup> A circular mil (denoted by cir mil or cm) is a term commonly used in electrical engineering to define cross-sectional areas of conductors. It is the area of a circle one mil (or 0.001 in.) in diameter. Such a circle has an area of  $0.7854 \times (0.001)^2$  or  $0.000007854$  sq in. Thus a wire 10 mils in diameter has a cross-sectional area of  $0.7854 \times (0.010)^2$  or  $0.00007854$  sq in., which corresponds to 100 cir mils. Multiply square inches by 1,273,200 to convert to cir mils. The abbreviation cmf here indicates a wire 1 ft long, and 1 cir mil in cross-section.

Assuming that the allowable transmission loss may be 8 per cent, i.e., 400 watts, then 5400 watts must be supplied by the 120 volt source. The required current equals the power divided by the voltage,  $5400/120$ , or 45 amp. A conductor must have a very low resistance (and low resistivity, also, so that the area and weight may be held within practical limits) to carry 45 amp for 250 ft and waste only 400 watts as heating loss. The required resistance, according to Eq. 9.1, equals the power loss divided by the square of the current,  $R = W/I^2 = 400/(45)^2$  or 0.1975 ohm.

The conductor should be made of a good conducting material such as copper which has a resistivity of 10.37 ohms per cmf at 68 F. No temperature correction will be used for the conductor because its temperature varies over only a small range and changes more with the seasons than with service.

Eq. 9.2 is used to determine the cross-sectional area of a copper conductor for the transmission line. The known values are

$$\rho = 10.37 \text{ ohms per cmf}$$

$$l = 500 \text{ ft, total length of conductor}$$

$$R = 0.1975 \text{ ohm}$$

Substituting in Eq. 9.2 and solving for  $A$ :

$$A = \rho l / R = 10.37 \times 500 / 0.1975 = 26,300 \text{ cir mils, area}$$

The diameter,  $d$ , of the wire in mils equals the square root of the area in cir mils. Hence  $d = \sqrt{A} = \sqrt{26,300} = 162$  mils or 0.162 in. A diameter of 162 mils or an area of 26,300 cir mils corresponds to A.W.G. No. 6 for the size of the copper conductor.

The heating unit must be designed to have a relatively high resistance for it must dissipate 5000 watts, while the 500 ft of No. 6 copper wire dissipates only 400 watts. Copper wire of smaller diameter might be suggested, but the wire would have a very small area, for practical lengths, and it could not withstand the high temperature.

High resistance alloys, such as Nichrome, are also suggested since they are used commercially in heating devices operating at 1800 F. They have a high resistivity which permits use of reasonable cross-sectional areas with short lengths to obtain relatively high resistances.

The resistance of the heating unit at 1800 F is calculated by Eq. 9.1,  $R = W/I^2 = 5000/(45)^2 = 2.47$  ohms. The value of the resistance at 68 F as determined by Eq. 9.3 is  $R_t = R[1 + a(t - 68)]$ . If Nichrome is chosen for the heater, ( $a = 0.000095$  for Nichrome).  $2.47 = R[1 + 0.000095(1800 - 68)]$  and  $R = 2.47/1.165 = 2.12$  ohms at 68 F.

Tests indicate that a temperature of 1800 F can be attained by passing

45 amp through a coil of No. 12 Nichrome wire which has been close wound on a 0.190 in. diameter arbor, and is then stretched to twice its close-wound length.

The length of No. 12 Nichrome wire required to have 2.12 ohms resistance at 68 F can be calculated by Eq. 9.2. Now  $R = 2.12$  ohms,  $\rho = 675$  ohms per cmf, and  $A = 6560$  cir mils, hence  $l = 20.6$  ft. When coiled as noted before, the complete Nichrome heater will be a little over 5 ft long and will have 400 turns.

This example shows that a material with low resistivity (good conductor), copper in this case, is used to *transmit* electrical power with low losses. It also shows that a heating element should be made from a high resistivity material (poor conductor), Nichrome in this case, to *dissipate* the required power with a short length of reasonably heavy conductor.

**9.2. Skin Effect.** Direct currents distribute themselves uniformly over the cross-section of the conductor, and therefore use the center of the conductor just as effectively as they use the periphery. Alternating currents, however, owing to inductance effects within the conductor, crowd toward the outside of the conductor. This behavior is known as *skin effect*, and it raises the apparent resistance of the conductor because power loss varies as the square of the current, and the higher density of current flowing near the skin of the conductor produces more power loss than the lower density of current flowing through the center of the conductor saves.

The values of resistivity given in Table 9.1 are used to calculate the direct current resistance. The resistivity of the conducting material is unchanged by skin effect; only the total resistance of the conductor increases as the frequency of the current and the diameter of the conductor increase. This increase in resistance should not be neglected in very large conductors at commercial power frequencies and in most conductors at carrier and radio frequencies.

Since skin effect reduces the amount of current carried by the center portion of the conductor, hollow conductors are sometimes employed to more effectively use the material. Aluminum cable steel reinforced (ACSR) is used even more often than hollow conductors. This cable has a steel core which strengthens the cable, and an outer covering of aluminum which, because of skin effect and the high resistivity of the steel, carries most of the current. These conductors also have the advantage of a larger surface area available for cooling.

When conductors are run very close together, i.e., in a multiconductor cable or a conduit, a phenomenon similar to skin effect occurs; the current distribution in each conductor is disturbed by the currents in

the adjacent conductors. This phenomenon is known as *proximity effect* and is often more important than skin effect in increasing the apparent resistance of each conductor.

### INSULATORS

**9.3. D-C Resistance of Insulators.** Insulators are conductors of such high resistivity that the flow of current through them can usually be neglected. The dividing line between conductors and good insulators is so indefinite that they are usually separated by another group of materials which might be called semiconductors. These three groups, listed according to arbitrary limits of volume resistivity, are as follows:

Group	Volume Resistivity . ohm-cm
Conductors	$10^{-6}$ to $10^0$
Semiconductors	$10^0$ to $10^6$
Good insulators	$10^6$ to $10^{20}$

The flow of current through an insulator is called *leakage current*. This leakage current follows two parallel paths, one *through the body* of the insulating material, and the other *through the moisture film over its surface*. (See Fig. 9.2.) The resistance of an insulating material to leakage current through its body can be treated in the same manner as the resistance of conductors, and calculated by Eq. 9.2. This portion of the total leakage current depends on the size, shape, and volume resistivity of the insulating material.

The portion of the total leakage current which flows through the moisture film over the surface of the insulator depends to a great extent on the humidity of the surrounding atmosphere. Surface resistivity often decreases one million to one as the humidity increases from 25 to 90 per cent. The effect of humidity on surface resistivity also varies with the particular material.

The total resistance of an insulator is rarely calculated or measured because it changes so greatly with humidity and temperature that tests on two samples of the same material generally differ by at least 50 per cent and frequently by several hundred per cent. The insulation resistance of a complete motor, transformer, or cable, however, is frequently measured to indicate the condition of the insulation, i.e., whether it is dry and clean, moist and dirty, or damaged.

Insulating materials have a negative temperature coefficient of resist-

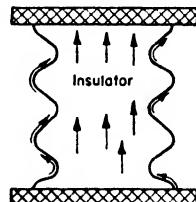


FIG. 9.2. Cross-section of an insulator.

ance, i.e., the resistance decreases as the temperature increases. For general purposes, the resistance of dry insulation may be assumed to be halved for each rise of 15 F.

**9.4. Dielectric.** A *dielectric* may be defined as a material having the property such that the energy required to establish an electric field in it is recoverable, at least in part, as electric energy. Insulators are dielectrics. The various properties they possess can best be illustrated by examples showing the effect of substituting various insulating materials between the same two conductors or electrodes.

Fig. 9.3 shows two electrodes, a copper conductor, and a lead cable sheath, separated only by air. The air is the dielectric. The conductor, the sheath, and the air between them form a capacitor. When a battery is connected to the electrodes of a capacitor, a current flows

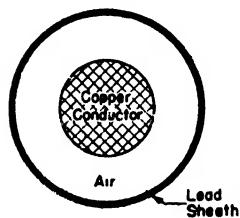


FIG. 9.3. Cable with air insulation.

until the capacitor is charged up to the same d-c voltage as the battery. An electric field then exists in the dielectric. Also a positive charge of electricity,  $+Q$ , appears on one electrode and a negative charge,  $-Q$ , appears on the other electrode. The *capacitance* of a capacitor is defined as the ratio of the charge  $+Q$  on the capacitor to the voltage  $V$  across it. The capacitance for a given set of electrodes depends only on the dielectric between the electrodes. The electric field in the dielectric and the charges on the electrodes of the capacitor will remain even after the battery is disconnected.

The electric energy stored in the dielectric can be released by connecting the electrodes together with a wire, effectively applying a zero voltage to the capacitor. Under these conditions the capacitor is discharged and the momentary flow of the charges produces a current through the circuit. This current which is transformed into heat when it flows through the wire is the electric energy recovered from the electric field set up in the dielectric.

A flow of current is produced whenever the voltage across a capacitor is changed. When an alternating voltage is applied to a capacitor, an alternating current flows through it because it is alternately charged in one direction, discharged, and then charged in the reverse direction. Neither the alternating nor direct charging current causes any energy loss in the *air* dielectric.

**9.5. Dielectric Strength and Dielectric Constant.** If only air were used as a dielectric in the cable, there would be no method of supporting the inner conductor with respect to the sheath. Also air has a *dielectric strength* of 56,000 volts alternating current per in. at 68 F, under atmos-

pheric pressure; i.e., it breaks down (ionizes) and becomes a conductor when the voltage across it exceeds 56,000 volts alternating current per in. If the voltage applied to the cable were, say, 66,000 volts alternating current, and the space available for insulation were only half an inch, the insulation must have a dielectric strength of at least 132,000 volts alternating current per in.<sup>1</sup> Treated paper has a dielectric strength of 300,000 volts alternating current per in., so that it could be used satisfactorily as an insulating material between the conductor and the lead sheath.

If the same battery were connected to the capacitor (Fig. 9.4) formed by the conductor, the paper, and the sheath, the charge built up on the electrodes would be greater than when air was the dielectric. The ratio of  $Q/V$ , which is defined as the capacitance, would have increased. The ratio of capacitance of a capacitor containing a given dielectric to the capacitance of the same capacitor with air as the dielectric is called the *dielectric constant*. Air, therefore, has a dielectric constant

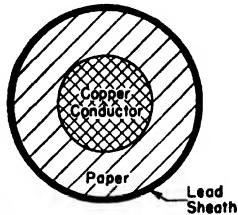


FIG. 9.4. Cable of Fig. 9.3 with paper insulation.

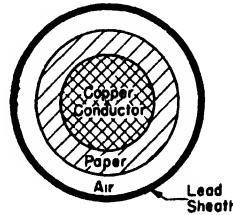
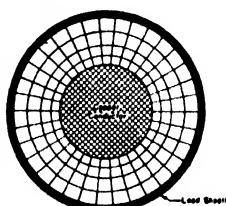


FIG. 9.5. Cable of Fig. 9.3 with air and paper insulation.

of unity. Certain treated papers have a dielectric constant of 3. Three times the quantity of charge, therefore, appears on the electrodes when they are insulated by this treated paper as when they are insulated by air. The a-c current for a given a-c voltage will also be three times as great with the paper as with air.

<sup>1</sup> A uniform voltage gradient is assumed in presenting this problem to allow the use of very simple mathematics. An actual flux plot or calculation of the voltage gradient would indicate that the air nearest to the conductor would be subjected to a maximum voltage gradient of 190,000 volts per in. The accompanying flux plot gives an indication of this high gradient since the concentric circles represent equal voltage steps.

The flux plot indicates that the material nearest to the conductor is subjected to the highest dielectric stress. A high dielectric strength material could be used next to the conductor, while a lower dielectric strength material could be used to advantage near the sheath, when both the materials have nearly the same dielectric constant.



One might then suggest economizing on paper with the arrangement in Fig. 9.5, which has a one-fourth inch thickness of paper wrapped on the conductor, capable of withstanding 75,000 volts alternating current. Air fills the remaining one-fourth inch radial space between the paper and the sheath. This arrangement is really two capacitors in series. To better visualize this condition, assume a tinfoil wrapping on the outer surface of the paper. This tinfoil wrapping will have no effect because the outer surface of the paper is all at the same voltage even without the tinfoil. The conductor, the paper, and the tinfoil form one capacitor and the tinfoil, the air, and the sheath form the second capacitor.

The two capacitors are in series so the same current will flow through each of them. The thickness of each dielectric is one-fourth inch. The areas of the air and the paper will be assumed equal for these considerations. The capacitor with the paper dielectric has a capacity three times as great as the capacitor with the air dielectric. Therefore the paper capacitor will require only one-third of the voltage that the air capacitor requires for a given current through them. The voltages across the paper and the air will, therefore, be *inversely proportional to their dielectric constants*. One-fourth of the 66,000 volts between the conductor and the sheath will appear across the paper, while three-fourths of the 66,000 volts, or 49,500 volts, will appear across the one-fourth inch of air. In order to avoid voltage breakdown, the air would require a dielectric strength of four times 49,500 or 198,000<sup>1</sup> volts alternating current per inch under these conditions, which are worse than when air is the only dielectric.

The foregoing example indicates that when two dielectrics are used in series and both are to be used to the limit of their insulating ability, the dielectric with the lower dielectric constant is required to have a higher dielectric strength to withstand the higher voltage per unit thickness.

*Dielectric strength* is one of the most important electrical properties to consider in the selection of an insulating material. It is obtained for practical purposes by dividing the breakdown voltage by the thickness of the dielectric between the test electrodes.

Dielectric strength should never be given without specifying all the conditions of the test because all of the following affect its value to a very great extent.

In general, the dielectric strength decreases with increase in the

<sup>1</sup> Since this maximum voltage gradient for the air occurs midway between the electrodes, the value obtained in the text corresponds very closely to the value of 210,000 volts alternating current per in. given by more exact calculations.

*thickness of the specimen*, the total breakdown voltage being proportional to the two-thirds to three-quarters power of the thickness.

The dielectric strength decreases with increase in the *diameter of the electrode*. This condition is most pronounced in thin specimens because the relatively larger electrodes increase the possibility of including a flaw between the electrodes. This effect indicates that a large number of tests made with small diameter electrodes would give a large range of values for the dielectric strength of the material. A probability curve of the values so obtained would be of the form of curve *A* in Fig. 9.6.

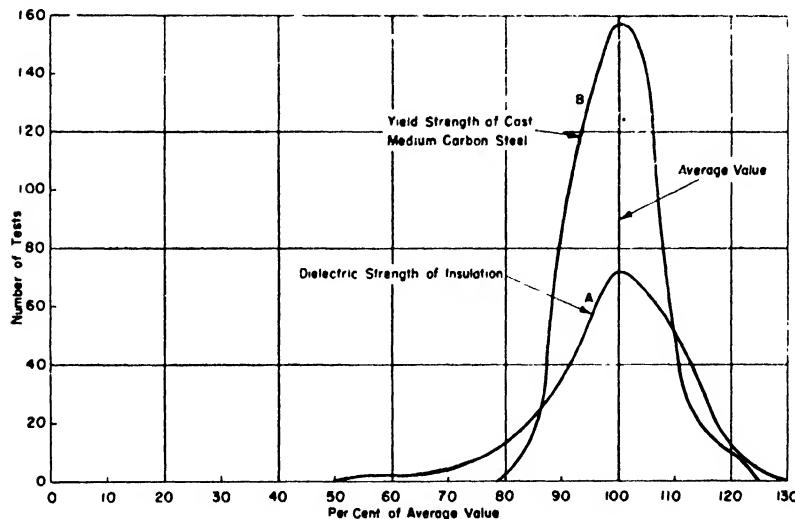


FIG. 9.6. Probability curves of yield strength of cast steel, and of dielectric strength of an insulation.

Some of the tests give a value of dielectric strength very far from the average value, but the extremes in the low direction exceed those in the high direction. The average test value is very much higher than any value that the designer can count on. Designers do not generally consider the property probability curves of materials they use. Usually no difficulties result because the chance variation of properties for most engineering materials is relatively small. For example, curve *B* in Fig. 9.6 is a probability curve of the yield point of cast steel. The curves for steel and insulation are plotted on the same coordinates, so that the unusually wide spread of values obtained for insulation is clearly evident. The probability curve of each particular insulation, together with all the conditions of the test, should be investigated whenever possible before using it in a design.

The effect of *time of application* of voltage on the insulation is shown in Fig. 9.7 for two different materials. The test voltage was applied in pulses with sharp-edged electrodes to produce *corona*.<sup>1</sup> The time of application of the voltage had only a small effect on the special corona-resistant insulation (curve A), while the dielectric strength of the ordinary insulation (curve B) decreased rapidly as the time of application increased.

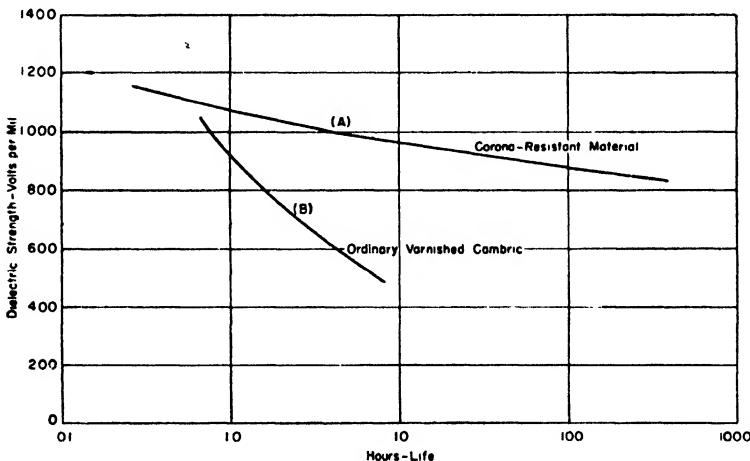


FIG. 9.7. Life of insulation versus pulse voltage (to produce corona).

The dielectric strength decreases with increase in the *frequency* of the applied voltage. This decrease is negligible for power frequencies up to 100 cycles per sec, but at radio frequencies it may drop to 10 or 20 per cent of its original value.

The dielectric strength generally decreases with increasing *temperature*, but the extent to which this occurs varies greatly with different materials. When materials are to be used at other than room temperature, their dielectric strength should be determined over their operating range of temperature.

The dielectric strength of insulating materials is considerably affected by the presence of *moisture* in the materials. Since the materials respond very slowly to changes in *humidity*, they should be kept at the desired humidity for several hours preceding tests.

**9.6. Dielectric Losses.** The paper insulation in the example had some losses which were not present when air was the dielectric in the cable. These dielectric losses vary with different materials, and, when the voltage is high, they have an influence upon dielectric strength.

<sup>1</sup> Local ionization of air in or around the dielectric.

In addition, they generally vary as the square of the voltage up to a certain dielectric stress, after which the loss begins to increase faster than the square of the voltage. This increase occurs when occluded gases begin to ionize.

The *power factor* of a dielectric is a measure of the dielectric loss with alternating current. It is equal to the power loss in the dielectric divided by the product of the voltage across it and the current through it.

The power factor, since it is a measure of the dielectric loss, remains constant up to a certain dielectric stress and then increases. In general, the power factor decreases with increasing *frequency*. The dielectric power lost, however, actually increases with frequency because the current is proportional to the frequency.

Traces of *moisture* in the dielectric or on its surface may cause a considerable increase in the power factor value. The amount of moisture depends on the humidity of the atmosphere and the length of time the dielectric has been exposed to it. *Temperature*, too, has an effect on power factor but its effect on different materials varies so widely that no general rule can be given.

**9.7. Arc Resistance.** The arc resistance of a material is a measure of the amount of carbonization (*tracking*) that occurs under a power arc. It is determined by drawing a high-voltage low-current a-c arc between two pointed tungsten electrodes resting on the surface of the material under test. The arc is increased at 1-min intervals until the material fails by becoming conducting. The time required to reach failure is a measure of the arc resistance of the material. In testing two materials, the difference in the length of time they withstand the arc should be in the order of two to one before it can be said that one is significantly better than the other. Arc resistance is of particular importance in switch design where proper materials choice and engineering can do much to reduce the danger of tracking.

**9.8. Conclusion.** The most important electrical properties of materials have been discussed in this chapter. Whenever materials are to be chosen for electrical apparatus, some or all of these properties must be considered. The electrical properties of the common electrical insulations and plastics, together with other properties of importance, are presented in the next two chapters.

#### REVIEW QUESTIONS

1. (a) Name three good metallic conductors of electricity and three which are relatively poor. (b) What nonmetallic conductors are important in engineering?
2. Calculate the area in circular mils of a copper bus bar  $\frac{3}{8}$  in. by 3 in. in cross-section. What is its resistance at 68 F in a length of 45 ft?

3. The resistance, per conductor, of a transmission line is 9.61 ohms, measured when the average air temperature is 42 F. If the expected extremes are -20 F and 90 F, what are the maximum and minimum resistances per conductor of the line? Assume the conductor temperature is the same as that of the air. ( $\alpha = 0.00218$  per °F at 68 F.)

4. Explain "skin effect" and "proximity effect" and tell how they affect the resistance of a conductor.

5. The resistance measurement on an insulator cannot always be duplicated. What external factors tend to change the effective resistance of an insulator?

6. Define "dielectric strength" and "dielectric constant."

7. Explain the dangers which may be encountered when two materials of different dielectric constant are used in series to form an insulator.

8. (a) What is the "power factor" of a dielectric? (b) Are dielectric losses larger in d-c, or in high frequency a-c circuits? Why?

#### REFERENCES

"Standard Handbook for Electrical Engineers."

"A. S. T. M. Standards on Electrical Insulating Materials," Committee D-9, 1942.

## CHAPTER X

### ELECTRICAL INSULATION

By A. J. SHERBURNE and S. H. PROFFITT

**10.1. Introduction.** The great variety of materials available today sometimes seems only to add difficulty to the engineer's problems of selection. To those unfamiliar with the field, this seems particularly true with respect to electrical insulation.

In Edison's day, the problem was quite the opposite. The first underground voltage distribution system used with Edison's incandescent light failed successively as wood, coal tar, a composition of powdered slate, and wrappings of muslin were tried. Success came only after extensive study by Wilson S. Howell, of the Edison staff, showed that a "cooked" substance of refined Trinidad asphaltum, mixed with oxidized linseed oil, paraffin, and beeswax was satisfactory as an insulating compound.

As engineering requirements for specific properties have developed and broadened, many new insulating materials have appeared, until today the field has become highly specialized and very important. This chapter includes a classification of the present insulation materials based on allowable operating temperatures. Typical applications are given to show how the materials are combined and applied to produce insulations for electrical apparatus.

#### PROPERTIES

**10.2. Properties Required.** Electrical insulating materials are defined as materials which offer a very large resistance to flow of current, and for that reason they are used to keep the current in its proper path along the conductor. The primary purpose of insulation is therefore electrical, and in the early days of the electrical industry this was the only purpose. As service requirements have broadened, insulation has gradually assumed a thermal, mechanical, and even chemical burden as well. Often properties to meet such secondary requirements are so necessary that they, rather than the electrical properties, limit the choice of material. For example, heat resistance is essential in heating devices; resistance to aging under heat is required in power apparatus; arc resistance in switchgear and control apparatus; high mechanical

strength in rotating machinery; toughness to resist shock as in equipment for naval applications; definite hardness to provide uniform wear as desired in commutators, or to resist wear as in dead segments of rheostats; flexibility for insulation on wire and cables; chemical stability in severe atmospheric conditions; and appearance as required in appliances.

Thorough consideration of operating conditions will go far toward solving an insulation problem. But manufacturing methods can nullify the best materials. Proper care must be taken not to injure the insulation by tearing, abrasion, scorching, etc. Unfortunately no rules can be given upon which the engineer may base his selection of an insulating process; experience or application tests must be his guide. Tests of this kind, demonstrating the influence of methods and processes on insulation, are often as important as the properties of the material selected. This should be kept in mind throughout the following discussion of properties.

For convenience, the various properties are grouped as electrical, thermal, mechanical, and chemical.

**10.3. Electrical Properties.** The selection of an insulation depends on the relative importance of dielectric strength, insulation resistance, surface conductivity, power factor (dielectric loss), dielectric constant, and arc resistance. It is important that each of these terms be self-descriptive before the reader proceeds in this chapter. They are the electrical properties of an insulating material and are discussed in Chapter IX.

**10.4. Thermal Properties.** Insulation breakdowns are most frequently the result of internal heat and moisture. The heating causes chemical changes in the insulation which are aggravated by the presence of moisture. It is for this reason that the thermal properties are second only to electrical properties in importance for the average application. Heat aging, thermal conductivity, thermoplasticity, thermal expansion and contraction, and inflammability are the thermal properties which must be considered.

*Heat Aging.* Aging is in effect the wearing out of an insulating material by reducing its resistance to mechanical injury. It increases rapidly with temperature, approximately doubling for each increase of 10 C. Such increases in temperature cause dehydration of all cellulose materials and an intensification of oxidation and other chemical changes in both cellulose and varnish substances. These are the effects that lead to brittleness, cracking, shrinking, and, under vibration and stress, ultimate crumbling and disintegration (see Fig. 10.1). Electrically, the material does not wear out until electrical breakdown occurs; thus

aging may progress quite far before a mechanical movement breaks the brittle insulation sufficiently for voltage puncture.

The standard test for heat aging has been strictly a flexibility test preceded by aging in an oven at elevated temperature. For example, this test for varnish may consist in aging a varnish-on-metal film at 105 C until a bend around a one-eighth inch mandrel cracks the film.

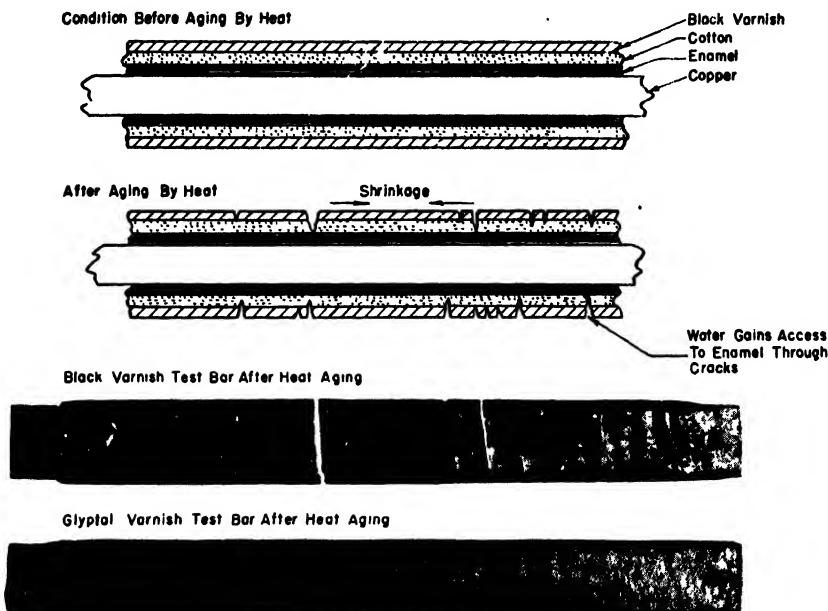


FIG. 10.1. The effect of heat aging on varnish insulation.

Flexibility, however, has been found to have little to do with the actual life of a varnish in a winding or coil. Two identical bars were covered, one with the old, black oil-base varnish insulation and the other with a newer Glyptal varnish insulation (Fig. 10.1). In the flexibility aging test the old varnish proved best. However, after the bars were heated at 150 C for a period of several weeks and not flexed, shrinkage and oxidation caused severe cracking of the originally flexible black oil-base varnish, while the heat only seemed to toughen the Glyptal coat. Thus the flexibility aging test, while it may be useful in measuring the integrity of a finish coat under exposure to air and heat, has little value for a coil or motor winding application without the confirming evidence from the other test.

*Thermal Conductivity.* Insulating materials must often serve as heat conductors. The internal temperature of a winding depends upon the

heat which can escape through the insulation to the surroundings, and therefore a well-bonded compact coil is better than one having porous, air-filled insulation of low over-all thermal conductivity.

*Thermal Plasticity.* In any winding, pressure on the wires varies under operating conditions because of the expansion and contraction of the parts of the machine in which the winding is used, caused by variations in temperature. Although, in practice, pressure generally is accompanied by slight vibratory motion and consequent abrasion, it is valuable to observe the flow of wire insulation at high temperatures in the absence of vibration. For this purpose a device is used which subjects a crossed-wire sample to pressure at elevated temperature, while 125 volts direct current are applied. The material under test insulates the wires, and proper care is taken to prevent grounding or shorting elsewhere. The results of this test are indicative of the resistance of the material to failure caused by pressure or flow of film. Actually a high degree of thermoplasticity may be unimportant in many applications or even of considerable benefit, so it should not always be viewed with disfavor.

*Thermal Expansion and Contraction.* Where an insulation will be subjected to wide temperature variation, the thermal expansion and contraction characteristics of a material may be the limiting factor in selection. Usually, however, the temperature variation will be low enough to make these properties unimportant except when using filling compounds or large masses of material.

**10.5. Mechanical Properties.** Insulations are regularly tested for impact strength, tensile strength, hardness, toughness, elongation, flexibility, adhesion, and abrasion resistance. In addition there are certain other mechanical properties uniquely important to varnish products. These are bonding, penetration, and through-curing.

*Bonding.* Bonding is the degree to which a compound binds the insulating material and wires into a solid mass. In rotating armatures considerable stress on insulating materials is caused by centrifugal force. The insulating material should not deform plastically and break the bond of wire to wire under such treatment. Furthermore, heat from the windings must be dissipated through the insulation to the surroundings. Thus bonding serves two functions; it binds the conductors together, thus minimizing movement and consequent abrasion, and it also improves the heat conductivity of the conductor mass. Bonding strength is typically listed as high, medium, or low.

*Penetration.* Penetration is the degree to which a compound will permeate its supporting structure and may be recognized as a generalized function of viscosity, surface tension, and the ability to wet the struc-

ture. In material specifications its value is also frequently listed as high, medium, or low.

*Through-Curing.* Through-curing is the ability of a material such as varnish to harden through a mass. Oxidation is at a minimum inside a coil, and hardening, or *curing*, as it is traditionally called, is most difficult. Therefore, the special property of *through-curing* becomes important. Material specifications also describe this property in terms of high, medium, or low.

**10.6. Chemical Properties.** The resistivity of an electrical insulation to deleterious action by water, oil, ozone, corrosive vapors, acids, alkalies, and certain other chemicals is a major factor affecting insulation life under the wide variety of uses in the chemical, paper, petroleum, and metals industries.

*Effect of Water and Tropical Tests* Water directly lowers electrical properties, such as electrical resistance and dielectric strength. The water may be transmitted through an outside coating and cause damage inside, it may be directly absorbed by an insulating material, it may cause a chemical change of the insulation itself, or it may drastically lower the surface resistance of an insulator.

Water will pass less than half as fast through a film made with the new phenol-oil type of varnishes as it will pass through the old type of varnishes. No varnish, enamel, lacquer, or paint film is 100 per cent water impervious, however, and moisture resistance and water repellence depend a great deal upon the degree of cure of the film, and upon the character of the film-supporting material. The most absorbent supporting materials are cotton, paper, and asbestos, the water being soaked up by wick action of the fibers. For this reason, under moist conditions they should be used with caution.

A useful test of the effect of water absorption on electrical properties is a dielectric strength test after 24 hr in water at 25 C and 85 C. When compared with a dry-material dielectric strength test, the best water-resistant varnishes show not more than 25 to 30 per cent drop in volts-per-mil breakdown after remaining 24 hr at 25 C. The minimum dielectric strength after such a test is specified as 300 volts per mil for air-drying varnishes and 400 volts per mil for baking varnishes.

As a measure of the chemical stability in water, two tests may be used. In one, rods or strips are coated with a standard insulating film thickness and immersed in water until the leakage of current reaches a specified value. In the second, the so-called "tropical test," varnished cloth samples are exposed to the deleterious action of steam and water in a pressure cooker at 100 to 120 C.

*Acid and Alkali Resistance.* Resistance to weak acids and alkalies

is tested by submerging coated test samples (strips or rods) in a 10 per cent acid or 1 per cent alkali solution and measuring the leakage current and time required before complete failure occurs.

*Oil Resistance.* A difference should be noted between oilproofness and oil resistance. *Oilproof* materials are those which are unattacked by oil, while *oil resistant* materials are those which protect against oil though they may become soft.

*General.* Any insulating material which is likely to come in contact with ozone, corrosive vapors, or special chemicals should be thoroughly tested under exposure to these substances before assurance can be had that the material will perform satisfactorily as an electrical insulation.

### CLASSIFICATIONS

**10.7. Temperature Classification.** The materials ordinarily employed in insulations include cotton, silk, paper, rubber, wax, resins, asphalts, compounds, natural-resin varnishes, synthetic-resin varnishes, plastics, mica, glass, asbestos, porcelain, pure oxides, the dielectric liquids, petroleum oils and synthetic oils, and the dielectric gases, hydrogen, dichlorodifluoromethane (a gas used as a refrigerant), nitrogen, and air, which is perhaps the most important of the gases.

Classification according to state, though undoubtedly the most obvious classification, is of little informative value and might easily cause misunderstanding because several of the insulations, for example, are applied in the liquid state but serve as insulation in the solid state. Recognition of the potential danger of heat to insulation is given in the A. I. E. E. standards in which the insulating materials are classed according to their permissible operating temperatures. These classifications are defined in Table 10.1.

The limiting temperature is supposed to be at the hottest point, and, for coils, is arbitrarily taken as 15 C higher than the outside surface. Thus a Class *O* material may be used in a coil which is to operate with a surface temperature of 75 C. It follows that with an ambient of 40 C, a surface-temperature rise of 35 C is permissible, or a winding temperature rise of 50 C can be allowed.

It must be emphasized that the materials themselves were classified with reference to past experience in the field, following which a certain maximum temperature was assigned to each classification. Though test data might show that a few of the Class *A* materials are reasonably satisfactory for certain applications at temperatures of 200 C, this does not mean that such materials fall into Class *B* or Class *C*. Recognition

of situations such as this have been made in the A. I. E. E. standards for specific electrical apparatus. The foregoing classification and accompanying maximum temperatures have been selected for purposes of standardization only. In some localities building codes and underwriters' specifications may call for even lower temperatures.

TABLE 10.1. A. I. E. E. CLASSIFICATIONS OF ELECTRICAL INSULATION<sup>1</sup>

<i>Class</i>	<i>Assigned limiting insul temperature</i>
<i>O</i>	Class <i>O</i> insulation consists of cotton, silk, paper, and similar organic materials when neither impregnated nor immersed in a liquid dielectric. 90 C
<i>A</i>	Class <i>A</i> insulation consists of: (1) cotton, silk, paper, and similar organic materials when either impregnated or immersed in a liquid dielectric; (2) molded and laminated materials with cellulose filler, phenolic resins, and other resins of similar properties; (3) films and sheets of cellulose acetate and other cellulose derivatives of similar properties; and (4) varnishes (enamel) as applied to conductors. 105 C
<i>B</i>	Class <i>B</i> insulation consists of mica, asbestos, fiber glass, and other inorganic materials in built-up form with organic binding substances. (A small proportion of Class <i>A</i> materials may be used in Class <i>B</i> applications for structural purposes only.) 130 C
<i>C</i>	Class <i>C</i> insulation consists of mica, porcelain, glass, quartz, and similar inorganic materials not used in construction with a material from the other classes. No limit selected.

<sup>1</sup> For a worth while and detailed discussion of this classification and other insulation standards, the reader is referred to A. I. E. E. Standards No. 1.

Actually, these standards are conservative today, especially since the advent of the newer synthetic resin varnishes. Often it is possible to use coils at somewhat higher temperatures and still have what may be considered adequate service, as long as cellulose materials such as paper and cloth are prevented from dehydration and oxidation by a good varnish film. For example, there have been instances when coils, insulated with cotton and treated with synthetic resin varnish, have withstood peak temperatures as high as 300 C for a very short time without serious injury, whereas cotton or paper would have been entirely burned at a much lower temperature.

The foregoing A. I. E. E. classification includes only those insulating materials used as solids. The oils and gases are not included. They will be grouped separately.

**INSULATING MATERIALS**

**10.8. General.** Electrical insulating materials are used for wire coating and cable construction, for insulating spacers and structural purposes, and for coil and motor winding applications. For convenience they are grouped as (*a*) thermo-classified dielectrics (Classes *O*, *A*, *B*, and *C*), (*b*) dielectric liquids, and (*c*) dielectric gases.

**10.9. Class O Dielectrics.** (1) *Untreated Cotton.* Untreated cotton is used principally in the form of cloth or tape. In this form, it is flexible, capable of close wrapping, possesses good mechanical strength, and readily absorbs insulating varnishes and compounds. When used for covering wire, either as a single or double covering, it requires relatively little space, and at the same time provides mechanical protection during coil winding and acts as a base to which varnish may be applied to help bonding of turns.

(2) *Silk Cloths and Tapes.* Because of high dielectric and mechanical strength, silk cloths and tapes are used where small thickness or low space factor is important, as in meters and instruments.

(3) *Untreated Paper.* Untreated paper, applied in a special wrapping of thin tape, is used as a spacer between layers of certain types of control coils and transformer windings and as an insulation for high voltage cables. Fibers and pressboards are used in sheet and tape form for wrapping conductors, for separators, slot armor, etc., and to provide a mechanical protection and backing for other insulation.

(4) *Rubber.* Rubber is used largely for cable and lead wires, but with improvements in rubberlike synthetics and their methods of application, the use of rubber as an insulation may gradually disappear. Rubber is damaged by heat, ozone, and oil, but it has good abrasion and water resistance.

(5) *Waxes.* Waxes, because of their high surface resistance (electrical), exceptional water repellence, and good dielectric constant, have been used as impregnating compounds in condensers and high tension coils of various kinds. The commonest wax is paraffin, which has a dielectric constant of 2; chlorinated naphthalenes have a constant of 6. The waxes are included here because of their low melting point (50 to 100 C.).

**10.10. Class A Dielectrics.** (1) *Natural Resin Varnish.* The most important substances from the point of view of life and dependability of electrical apparatus are the insulating varnishes. They are manufactured from suitably prepared vegetable and animal oils, natural gums or resins, synthetic resins and pitches, or asphalts, thinned to a proper working consistency with solvents. Usually they are classed as clear or black varnishes, the former now including a wide range of

different natural, and oil-modified, synthetic resin varnishes, and the black being asphaltic base materials. Varnishes are also classed as to their drying properties and uses, e.g., air drying, quick baking, plastic, etc.; finishing, impregnating, etc.

The correct terminology for paints and varnishes is graphically illustrated in Fig. 10.2. One outstanding exception to those definitions should be noted: varnishes used for coating wire are usually called *wire enamels* though they normally contain no pigment.

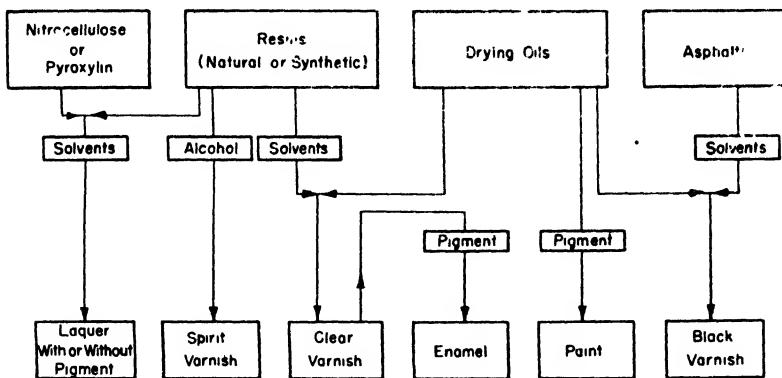


FIG. 10.2. Terminology of paints and varnishes.

**NATURAL RESINS.** The natural resins, or "gums," include shellac, rosin, Kauri, Manila, Congo copal, and many others, most of which are found in India or the East Indies. They are gums or pitches which exude from trees, or bugs (for shellac), or from fossil accumulations which come from fossilized trees. Shellacs and copals, especially, are graded according to hardness and solubility, but they vary considerably in dirt and impurities, and from lot to lot in properties and workability. It was this lack of uniformity and difficulty of handling which gave synthetic or chemically prepared resins their chance.

Rosin and ester gum may also be classed with the natural resins. Rosin, a product of pine pitch, is a hard, brittle resin which melts at 80 or 90 C. It has a wide range of application, but for varnishes its use alone is limited by its softness and lack of durability and its high acidity. Ester gum is a product of the high temperature reaction of rosin and glycerine. It is much less acid than rosin and more weather resistant and flexible in a varnish formulation.

**DRYING OILS.** A drying oil is an extract from animal fat or from a vegetable seed or nut. It is characterized by its ability to take up oxygen from the air and convert to a solid film by the double process of

oxidation and polymerization. This last term, without going into too much detail, can be defined as a process in which small molecules (monomers) unite with one another to form relatively giant molecules (polymers) either in the form of long chains or cross-tied complex structures. In contrast with the monomers, the resulting solid polymers have higher heat, solvent, and moisture resistance as well as markedly improved mechanical and dielectric properties, all of which are essential to a good insulation material. Though some materials will polymerize directly, the drying oils must first undergo oxidation by the absorption of oxygen from air.

Many drying oils have been isolated, but only a few are important for varnish and enamel making. The main ones are linseed, perilla, oiticica, and chinawood oils. Linseed oil is the most familiar and the oldest in history. It is derived from flaxseed by pressing or solvent extraction. Chinawood oil comes from a nut resembling a huge horse chestnut, the fruit of the Chinese tung tree. Linseed oil is much slower drying than chinawood or oiticica oil and imparts flexibility and life to films, whereas "wood" oil gives toughness and improved water and chemical resistance. Most important of all, particularly for coil treating varnishes, chinawood and oiticica oil have the almost unique property of setting up rapidly to a gelatinous mass throughout a very thick layer or film. Less oxygen and heat are required for this change than with linseed oil. Recently a process has been developed by which the non-drying castor oil is converted into a drying oil. This "dehydrated castor oil" is becoming increasingly important in industry.

The terms "short oil" or "long oil," relating to the "length" of a varnish, designate the number of gallons of drying oil to every 100 lb of resin. A short oil varnish is about 10 gal in length, and a long one may be 70 or 80 gal in length.

The rate of drying of an oil is, of course, connected with the amount of oxygen it can absorb and its chemical structure, but it is not dependent upon these factors alone. The rate also depends upon temperature, light, hygrometric (moisture) conditions, and upon small quantities of accelerating catalysts, called driers. Driers are organic salts of metals, such as cobalt, manganese, and lead, which act as oxygen carriers or catalysts and greatly speed up the polymerization. Very small amounts (a few tenths or hundredths of a per cent) are sufficient for maximum effect. Too much drier often impairs durability and life of the film or may act as a retarder rather than an accelerator.

**ASPHALTS AND PITCHES.** For black varnishes, the asphalts or pitches play the same role as the resins do in clear varnishes; they may even be used together with resins. Among naturally occurring asphalts (which

are mined, much as rock minerals, from veins) are gilsonite, a hard, brittle, substantially pure asphalt, and various softer, more plastic materials, such as come from the famous asphaltic lake in Trinidad. There are also available various pitches, which are the end products of the distillation of petroleum, coal tar, wood, and various vegetable oils and fats, chief of which is stearin pitch.

The pitches vary greatly in solubility and melting point or flow point. Some may be modified to give increased elasticity and stability by blowing with air while at high temperature. Their stability in a varnish blend depends greatly upon the cooking and upon the thinner used. The literature abounds with contradictory statements as to the value of asphaltic materials. They are susceptible to oxidation and are affected by light and heat, failure occurring by the progressive development of fine cracks. When the film is intact, the asphalts are excellent in acid and moisture repellence but are very soluble in oils. When added to clear varnishes, asphalts retard the drying considerably, unless they are used in sufficient quantity to give additional hardness themselves.

**SPIRIT VARNISHES.** Spirit varnishes are solutions of shellac, rosin, and other resins in alcohols; usually they contain no oil. They dry chiefly by evaporation of the solvent and are used for quick finishes, sizing, and coating of paper. Some synthetic resins in solution are also used as spirit varnishes. Shellac can also be made to melt under heat and to set thermally. However, in the molding of slot portions of coils using shellac coated paper spacers, the resin melted under the heat of the mold is generally solidified by cooling the mold, instead of waiting the necessary 4 to 48 hr required to cause the shellac to thermoset.

(2) *Synthetic Resin Varnishes.* In the last 20 yr synthetic resin development has produced outstanding resins of several types which are replacing natural resins in varnishes and "enamels" where quality, uniformity in composition and performance, and ease of manufacture are factors. The more important and successful types now in use are the phenol formaldehyde type of which Bakelite is perhaps the best known example, and the alkyd type, of which Glyptal is an example.

**ALKYD VARNISHES.** The chemistry of synthetic resins is elaborate and complicated. The simpler alkyd varnishes are mere mixtures of dissolved resin and drying oil, but the more useful have drying oil combined chemically with the resin itself (oil-modified resin). The alkyd resin varnishes may be so formulated that application of heat causes a permanent hardening of the resin to an infusible state, by the process known as *heat-polymerization*.

Alkyd resins, especially those modified with drying oils, have become some of the most important synthetic raw materials for finishes and

coatings because of their outstanding gloss, generally superior adhesion, and good durability. In the insulation field they have been slower in gaining importance but today they are gradually replacing the old black varnishes and compounds. The alkyds are acid, oil, and chemical vapor resistant and have generally good impregnating properties. When confined in pockets, they are difficult to dry out but they have excellent aging properties under heat. They are also excellent in arc and creepage resistance.

**PHENOLIC VARNISHES.** Oil-modified phenolic varnishes (in which the oil has reacted with the resin) have met with considerable success in insulation practice. These synthetic varnishes have excellent insulating, and good bonding and film building properties. In addition to their electrical insulating function, they may be relied upon to serve as an excellent protection against salt water exposure.

**FORMVAR ENAMELS.** Chief among the synthetic resin "enamels" which are replacing the drying oil type for magnet wire insulation are those formulated on the basis of a polyvinyl formal known as Formvar. Wire coated with these enamels has outstanding film adhesion, flexibility, and extensibility, as well as toughness and ability to take impact stretching and mechanical abuse. It also has good heat and solvent resistance. These properties have permitted its ever increasing use as insulation applied directly to the conductor where it is needed, thus eliminating or at least greatly simplifying the need for varnish treatment.

(3) *Other Synthetic Materials (Plastics).* There are other molded synthetics, laminated and sheet synthetic materials and synthetic insulation tubing which are of outstanding importance in the insulation field. These are the cellulose esters (cellulose acetate), Cellophane, the phenolics, the vinyls, and the styrenes. The reader is referred to Chapter XI for a discussion of these plastics.

(4) *Treated Cloths, Tapes, and Papers.* Treated cloths and tapes have advantages which make them particularly useful in electrical insulation. They possess a high degree of flexibility and mechanical strength, and may therefore be wound tightly in place in various motor coils, windings, lead and cable applications. As a class they have a high dielectric strength per unit thickness and some varnished cloths have a fairly low power factor and good aging characteristics. Paper is also varnish treated and used for applications similar to those for treated cloths.

(5) *Compounds.* Under this heading are listed solid, plastic, or semi-liquid materials which contain little or no thinner. They may be resins, asphalts, waxes, or varnish bases, or blends of these materials, and

may contain fillers, such as talc, silica, quartz sand, mica dust, slate, asbestos, and whiting. Because of this great variety no classification can be considered exact, but the materials are grouped, for convenience, according to their uses as sealing, filling, or treating compounds.

Sealing and filling compounds are used for protection of windings and for filling cavities in metal, porcelain, and other materials to exclude moisture, dust, and dirt. They may be either solid compounds which are melted and poured in place, solidifying on cooling, or plastic or puttylike compounds (such as are used in armature and field coils) which gradually set to a firm condition, with or without heat, according to the particular compound. For filling cavities and for similar operations, it is important that the shrinkage, especially at low temperatures, be as low as possible or as nearly as possible like that of the material with which the compound is in contact, and that the adhesion be good and cracking eliminated. For sealing compounds used on windings, their impact strength, thermal conductivity, and aging at elevated temperatures are also important properties. Oil, water, acid, and alkali resistance are also important requirements in certain applications.

Treating compounds are extensively used in producing a solidified mass from which moisture and air are excluded. Coils from which all moisture has been exhausted by a vacuum process are filled with melted asphalt compounds and rendered rigid and moistureproof. A compound for this application should be sufficiently tough to withstand rough handling and have a uniform flow point with a good degree of fluidity and penetration at the treating temperature.

(6) *Special Insulations.* A number of materials are now used to regulate the distribution of voltage stresses across the surface or through the body of insulation by means of controlled resistivity (e.g., "Rescon," named from resistor and conductor). In general these materials are used on or in insulation to increase the voltage at which corona will start or "arc-over" will take place, to increase dielectric or puncture strengths of insulation, or to grade potentials. The proper use of Rescon has in some cases raised the voltage at which corona starts from 3.8 to 50 kv, reduced creepage distances from 18 to 6 in., and increased dielectric strength 20 to 40 per cent at 60 cycles. Though these materials cannot accurately be classified as Class *A* owing to the wide scope of their application, it has been thought best to introduce them here.

**10.11. Class *B* Dielectrics.** (1) *Mica.* Mica comprises a group of natural silicates distinguished by highly developed cleavage. Pasted mica products for use in insulation are made from mica splittings laid in layers on paper or cloth backing and held together with a flexible binding cement or varnish, shellac and alkyd varnish being most satis-

factory. Mica tape is used in building up the larger sizes of armature bars and in Class *B* coil insulation. It is wound on coils in the same manner as varnished cloth tape. Flexible or rigid mica sheets are also made with suitable binders. One use is as insulating segments in commutators.

Unpasted mica is the only flexible insulation that is entirely unaffected by moisture. It has a high dielectric strength and very low dielectric power loss. Being an inorganic silicate, it has temperature resistance up to 450 C and is unattacked by acid and alkalies. It is the most generally satisfactory insulation known, but it is more expensive than other insulations because of the labor of obtaining it in split form. White (hard) mica is the type most widely used because it is cheaper and has these superior mechanical and electrical properties. Amber (soft) mica is used where its resistance to high temperatures or its softness is of importance.

Because mica is most commonly used in a pasted form, it has been included with the Class *B* materials.

(2) *Glass*. Glass has long been used for low voltage insulators, for lamps, etc., but only recently has it become possible to use it in a flexible fiber form as asbestos and cotton are used. During the last few years, the glass companies have developed a new method of producing fine fibers in quantity as small as 0.00025 in. in diameter. These fine fibers can be spun into thread and woven into cloth and tape. The fiber is both flexible and extremely strong, but when rubbed will abrade rapidly. The bundles of fibers in each thread of glass fiber make it porous, thus limiting the dielectric strength to that of the spacing. These disadvantages make it necessary to varnish treat the glass, which of course immediately lowers its high temperature resistance and places it out of the strictly inorganic class into that of the other Class *B* materials. Treated glass tapes have good electrical properties and water resistance but are not the equal of mica.

Generally, the use of glass fiber insulation is limited to the mechanical backing of mica or to low voltage insulation. Its widest use is in place of cotton or asbestos on magnet wire. It is high in cost but it is of interest for uses where space factor is important, and stability at high temperatures and in corrosive atmospheres are requisites. In Class *B* applications, advantages of glass as compared with asbestos are those of space, superior heat conductivity, and superior dielectric strength in moisture when properly treated.

The trend to Class *B* insulations with higher running temperatures and greater output for a given weight of motor may make glass even a more important motor insulation than it is today. Glass has also made

its appearance in high voltage insulators, e.g., glass transformer bushings with sealed-in metal flanges for subsequent welding.

(3) *Asbestos*. This mineral, which occurs in long fibers of fairly weak mechanical strength, has a relatively low dielectric strength and is only a fair insulation where the applied voltage is low. Its chief use is on high temperature windings, such as those in railway, crane, mill, or compressor motors, where severe overloads, together with wide ranges of ambient temperature may be encountered. Asbestos is also used on wire for electric heating devices such as welding machines, ovens, and electric irons.

(4) *Silicone Resins*. Recently it has been found possible to increase the maximum permissible temperature of Class *B* insulation by using special synthetic resins of a predominantly inorganic character. These *silicone resins*, as they are called, have the basic silicon-oxygen framework of the silicate minerals and glass, but have organic groups chemically bonded to the silicon atoms, so that the substance has some of the solubility and flexibility associated with the common organic synthetics. The result is a class of chemical compounds which is thermally stable up to 260°C, yet can be applied as varnishes and cured in place. In combination with fiber glass, these compounds offer an extension of the Class *B* temperature limit, thereby permitting more compact design.

The silicone resins as a group are characterized by low electrical losses, by dielectric constants around 4, and by high dielectric strengths. Their resistance to acids is generally good, but they are not resistant to strong alkalies. Where extreme thermal stability is required, operating temperatures as high as 200°C or even 300°C may be permissible with certain types of these silicone insulations.

**10.12. Class C Dielectrics.** Mica, glass, and asbestos are Class *C* materials but, when used with a Class *A* binder, form the intermediate group, Class *B*, and as such have already been discussed. There are other inorganic materials which find specialized application in the insulation field, particularly for high voltage and high temperature.

(1) *Porcelain*. American electrical porcelain is a ceramic product made up of clays, quartz, and feldspar. Part of the clay is used to regulate the plasticity of the mixture before firing, the rest to serve as a binder; the quartz is used as an aggregate or filler; the feldspar acts mainly as a flux. The hardness, refractoriness, and imperviousness of porcelain make it an excellent, weather-resistant, high-voltage insulator which is practically indestructible. These characteristics, however, vary in degree according to the process of manufacture. There are three main processes — the dry process, the wet plastic process, and the wet casting process.

Dry-process porcelain is formed in steel dies by compressing the porcelain mixture while in the form of a damp coarse powder. Porcelain parts used in low voltage work are made in this way. By the use of the proper dies a large variety of designs and sizes can be produced.

Wet-plastic-process porcelain is manufactured by forming the porcelain mixture while in a plastic puttylike state into approximately the desired shape, drying to a certain point, and then imparting the final shape by turning on a lathe, jigger, or potter's wheel. Though by this process it is not always possible to secure the degree of accuracy attained with the dry process, the density, dielectric strength, and mechanical strength are considerably better.

Wet-casting-process porcelain parts are comparable to the wet-plastic-process parts in electrical and mechanical properties and at the same time cost less when a considerable number of the same parts are to be made. The porcelain parts made by this process are made in plaster molds from a porcelain mixture of a thick cream consistency. After the plaster has absorbed the water from the heavy cream and the porcelain parts have dried sufficiently, they are removed from the molds, further trimmed, grooved, etc., if necessary, and then dried.

The process of glazing for dry, plastic, and cast porcelain is the same. Though glaze may remarkably improve the mechanical strength of very small parts, it is doubtful that much over-all improvement is made in the average, high-voltage insulator. Glazing is mainly intended to give a smooth, easily washable surface.

(2) *Steatite*. Steatite is the name given to a fired ceramic product which contains a high percentage of talc (usually over 80 per cent; talc is a hydrated magnesium silicate) bonded with ceramic fluxes to a nonporous structure. Steatite may be extruded or molded dry, but it requires high pressure equipment in contrast to the pug mills used for porcelain. Steatite possesses low loss characteristics needed for high frequency applications.

(3) *Mycalex*. Mycalex, a ceramic product made of glass-bonded mica flakes, possesses a combination of properties found in no other insulating material. Though mechanically stronger than porcelain (except in compression), it is not as refractory, but is far superior in this respect to other molded insulations made with synthetic resins, shellac, etc. Mycalex is generally compression or injection molded, though it is successfully machined, and in thin sheets it may even be punched. Aluminum alloys may be cast around Mycalex without affecting it in any way. Its use is particularly advantageous where the requirements demand (a) high mechanical strength, (b) high dielectric strength and insulation resistance, (c) low losses at high frequencies, (d) arc resistance, (e) heat

resistance well beyond the critical temperatures for molded or sheet organic materials, and (f) a compact construction with metal inserts securely molded in place. A few examples of compression molded and fabricated Mycalex parts are shown in Fig. 10.3.

(4) *Oxides*. The mineral oxides which remain stable in air can be used in some applications for high-temperature electrical insulations. Titania (titanium oxide), thoria, beryllia, magnesia, and alumina are the oxides which have been found most practical. They may be very

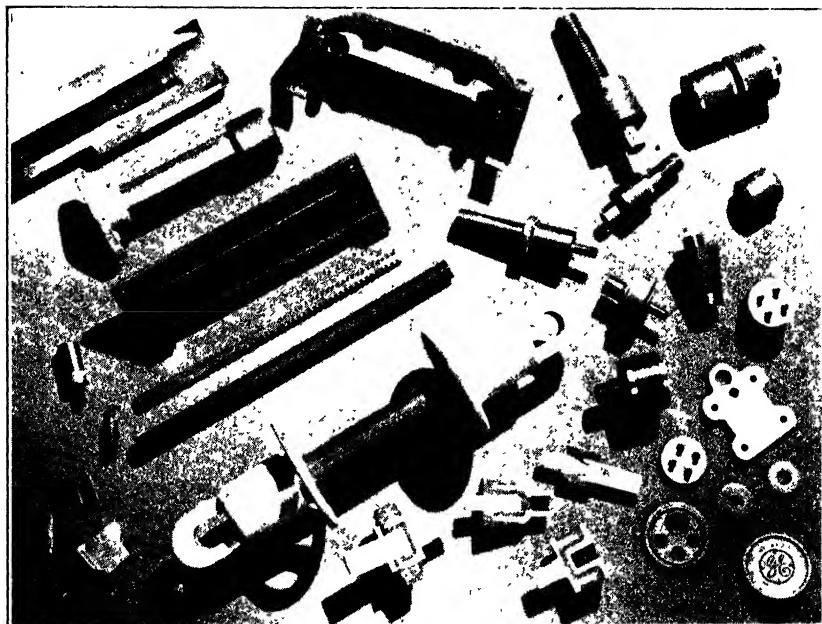


FIG. 10.3. Typical Mycalex parts.

finely divided and cast in molds using only water and a small amount of binder, or a thermosetting-plastic binder may be used which is later burned away. The difficulty of firing the oxides (at 2000 to 3000 C) makes their application very limited. One method of obtaining an oxide insulation which avoids this difficulty is anodizing. By anodizing aluminum, a heavy well bonded coating of aluminum oxide is formed which can be used intact as an insulation, but bending and abrasion are likely to cause electrical failure.

Many examples of insulators made of cast oxide powders can be found in electronic products. For example, condensers for push-button tuning devices have been built with titanium dioxide as the insulator. These condensers have exceptionally small physical dimensions because of the

particularly high dielectric constant (somewhere over 1000) of this oxide.

A high-temperature application of cast alumina is found in aircraft engine spark plugs. Not only does alumina offer higher heat conductivity and better high-temperature insulating properties than the porcelain it replaces, but it is also immune to the tetraethyl lead of high octane gasoline which attacks the silica in porcelain spark plugs.

TABLE 10.2. COMPARATIVE VALUES OF DIELECTRIC CONSTANT AND DIELECTRIC STRENGTH OF TYPICAL INSULATING MATERIALS

<i>A. I. E. E. Classified Dielectrics</i>	<i>Dielectric Constant</i>	<i>Dielectric Strength (volts/mil)</i>
Untreated paper (Nonporous cellulose)	2 6	120-125 ..
Varnishes		
Spirit	4-5	200-900
Oil	4-5	700-900
Asphalt	4-5	600-1200
Treated paper	3-4	500-550
Varnished cloth	3-4.5	900-1300
Laminated phenolic		
Paper base	4.5	900-1400
Cloth base	5.5	450-1000
Silicone resin	4	600-1000
Mycalex	8	245
Porcelain	6-7	40-280
<i>Liquid Dielectrics</i>		<i>kv/0.1" gap</i>
Mineral oil	2.2	20-40
Pyranol	4-4.5	35
<i>Gaseous Dielectrics</i>		<i>Dielectric Strength,<sup>1</sup> volts/mil</i>
		<i>0 lb/in.<sup>2</sup> g    50 lb/in.<sup>2</sup> g    100 lb/in.<sup>2</sup> g</i>
Air	1.00059	140    360    580
Nitrogen	1.0005	140    360    580
Freon	...	270    860    ..

<sup>1</sup> Crest voltage across a uniform field (for example, a field between two very closely spaced spherical electrodes). These values should be considered maximum for conditions as specified, because any irregularities, even dust, can cause a tremendous reduction. (For average equipment 75 volts/mil is often used.) The points listed all fall along a smooth curve but no extrapolation is permissible.

**10.13. Dielectric Liquids.** Mineral oils consist of a complex series of hydrocarbons obtained from refining crude oils. Among the most important uses are the cooling and insulating of transformers, regulators, and oil circuit breakers. A low viscosity oil is required in transformers and regulators for effective heat transfer and in circuit breakers for

rapid circulation during arc quenching. The dielectric strength, important in all applications, is greatly affected by the presence of certain impurities, principally water, and dissolved gases. It is very important to eliminate moisture from the oil and the part immersed.

In recent years, synthetic liquid dielectrics, called askarels (e.g., Pyranol, Inerteen, Chloroextol, Abestol), have replaced the mineral oils in some electrical equipment because in addition to the desirable characteristics of mineral oil, they have the additional property of being noninflammable.

**10.14. Dielectric Gases.** With the exception of the common use of air at atmospheric pressures (see Table 10.2), the employment of gas as an insulating medium has not reached the stage where it is of practical import to the majority of manufacturers of electrically energized equipment. Nevertheless, it is of interest to note that there have been developed a few important applications for gas insulation and the potentialities are such that gases should not be overlooked.

In place of oil an inert gas such as nitrogen has been introduced as an insulating medium in power cables (see Sec. 10.17).

A new high voltage X-ray machine extremely compact in size as compared with its predecessors utilizes dichlorodifluoromethane, a gas used in refrigerating systems, as an insulating medium. At the pressure employed, the gas has a dielectric strength several times that of air; thus 100 lb of gas does the work of approximately 12,000 lb of conventional insulating oil. This achievement has been possible only through careful design to insure uniform fields. The insulating value of compressed gas is critically dependent upon the electric field stresses; dust particles can often cause breakdown.

The application of hydrogen in synchronous generators and in condensers may well be mentioned here. Though the hydrogen is used principally to improve heat conduction and reduce windage losses, it also inhibits the deleterious effects (caused by the destructive action of the activated oxygen on insulation material) accompanying corona discharge in air.

#### SOME TYPICAL APPLICATIONS OF INSULATING MATERIALS

**10.15. Windings.** The two main types of windings for motors are random and form windings. Random winding refers to a winding process whereby the wire, usually round, is wound into slots; the wires lie in whatever position they happen to be laid down. Form windings are either formed to exact shape or are built up of rectangular conductors and bent to shape before being inserted into the slots. Size, voltage,

rating, efficiency, power factor, service requirements, and cost determine the choice of winding type.

Random windings are used in so-called closed slot motors, which include all the smaller sizes of fractional horsepower and induction motors. The wire insulation is generally "enamel," which may also be protected from mechanical injury by a bonded covering of paper or cotton. It is important that the windings be further protected from the sharp edges of the punchings by slot insulation made up of treated

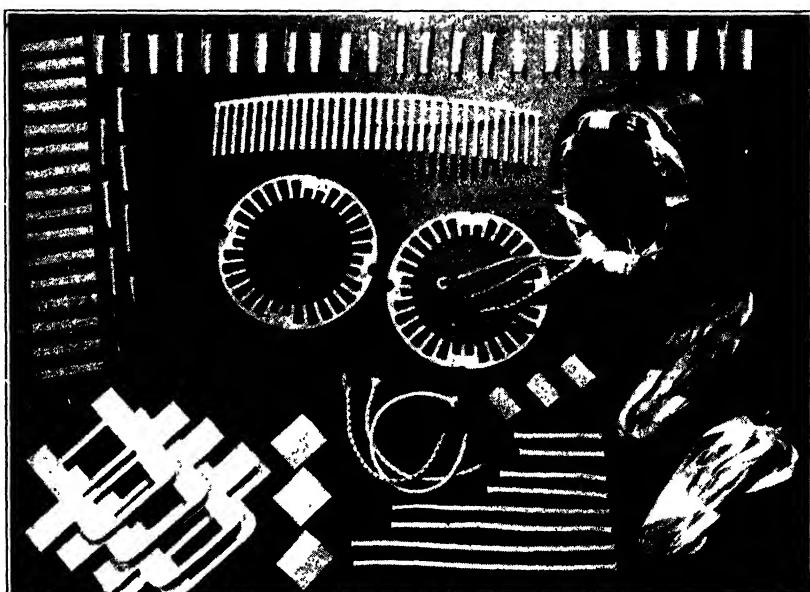


FIG. 10.4. Insulation material used in a random wound induction motor stator.

or untreated papers and varnished cloth. If phase insulation is needed, it usually consists of varnished cloth inserted between the proper coils. To provide a good tight fit, a processed wedge (wood, laminated-phenolic, or fiber) may be driven in over the windings and then a varnish treatment is applied to provide a solid bonding to the whole assembly (see Fig. 10.4).

Form windings used in small open slot motors are made of rectangular wire. The coil is first wound by machine into a lopsided loop or hairpin form (Fig. 10.5), varnish treated, the slot portion heat molded to size, and the coil then pulled out into the familiar hexagonal form. Form windings for large machines cannot be conveniently pulled, hence they are wound to finished form. After forming, the coils may be taped with

cotton, varnished cambric, fiber glass, asbestos, or mica and given one or more varnish treatments. When inserting the accurately formed coils in the proper slots, care must be taken to avoid mechanical injury by impact or abrasion and yet get as tight a fit as possible.

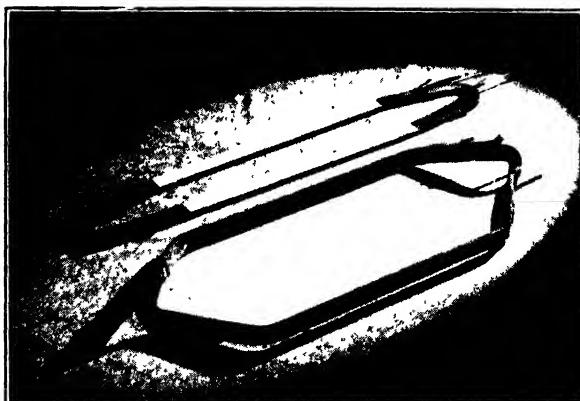


FIG. 10.5. Induction motor coils of rectangular wire before and after being "pulled out" and formed.

At 660 volts or higher the smaller sized induction motors use Class A insulation, but larger machines make use of a composite insulation, with mica tape on the inside and varnished cloth on the outside. The



FIG. 10.6. Large mica-insulated coil being taped.

mica tape adds greatly to the mechanical strength and ability to stand abuse, while the varnished cloth provides moisture resistance and also flexibility which is necessary to undergo the pulling and stretching of

installation. Where all-mica systems are required, mica tape is wound on the coil in the same way as cotton tape in the smaller machines (see Fig. 10.6). Class *B* coils made with asbestos or glass turn-insulation are used for railway motors and other motors subjected to overloads and high ambient temperatures.

Control coils of many varieties and uses are wound with bare enameled wire in layers, each separated by paper, the enamel being more than sufficient insulation for one turn. A varnish treatment further insulates the turns and layers and provides good bonding. Other control coils are random wound and certain high-current coils are wound edgewise with strap copper. These edgewise wound coils usually have several varnish coats directly on the bare copper. Asbestos, ground mica, or paper spacers are sometimes used, and the coils pressed down to size. Interpole coils, commutating coils, and some solenoid type coils are made in this manner.

**10.16. Varnish Treatment.** Clear varnish films are used for some insulation applications but in general varnishes are used in combination with reinforcing agents such as cotton, paper, mica, asbestos, and glass. The latter are bonded together by the varnish to form structures with improved heat and moisture resistance. The chief methods of varnish treatment are as follows:

- (a) Dipping:
  - 1. Without prebake.
  - 2. With prebake.
- (b) Vacuum filling.
- (c) Pressure filling.
- (d) Combinations of (b) and (c).
- (e) Brushing or coating (as coil is wound).
- (f) Use of pretreated materials.

They are all used in the impregnation of coils and will therefore be discussed in that connection.

Dipping is the oldest and simplest method of treatment. In filling a deep coil, it is least effective of all processes, but the penetration is materially aided by prebaking the structure to remove moisture.

Better penetration and filling are obtained by evacuating all air from a coil, in addition to removing the moisture, and then dipping before the vacuum is released. Still better results are obtained by following the vacuum cycle with a pressure cycle; i.e., while the coil is still submerged after the vacuum cycle the liquid varnish is put under pressure. Sometimes the pressure cycle alone may be used, the fluid pressure mold-

ing the insulation solidly to the conductors. These methods of course require larger initial outlay in equipment but eventually result in better and less expensive processes and products.

With materials such as drying-oil varnishes that depend on oxidation to harden, bulk filling results in tacky coils because oxygen is sealed out by the hard surface film. If use is made of the polymerization of chinawood oil, baking at high temperatures and for several hours time is required for hardening. At present a combination of phenolic-resin-hardening and chinawood-oil-polymerization provides the best balance between speed and temperature of hardening-in-mass to give required physical, chemical, and electrical properties for general practice.

In conjunction with hardening characteristics, a division is often made into spirit varnishes, air-drying varnishes, and baking varnishes.

Spirit varnish films are practically useless as electrical insulation because the brittle resin or gum base is usually incapable of undergoing oxidation or polymerization with accompanying improvement in mechanical and dielectric properties. The initial film obtained from them is soft and pliable owing to the solvent present, but when this evaporates the film becomes brittle and cracks, and may even granulate. In air-drying varnishes, the very thing that causes their rapid hardening is ultimately the cause of failure; the driers do not stop their oxidation process at the best place but continue on until the film becomes brittle or weak. Baking, when performed properly, removes the last traces of solvents and moisture and hence produces the most uniform surface. With synthetic resin varnishes, baking promotes the conversion of resin to an insoluble state and can produce in a few hours properties which are desirable from an insulation standpoint that weeks of air drying could not produce.

The hardening process is a complex one, and any insulating method must take into account the chemistry of the materials and insure that adequate opportunity is provided for the following: (a) Complete penetration and filling, (b) complete removal of solvent, (c) polymerization of the varnish to a hard or gelatinous state where optimum properties are obtained, (d) removal of volatile oxidation and polymerization reaction products as far as possible before surface setting takes place, (e) retention of maximum varnish base in windings, and (f) minimum injury to insulation on wire already in the assembly, either from heat, solvents, or mechanical forces.

At present, best results are obtained, in general practice, only by allowing sufficient time to accomplish these effects.

The ideal filling or impregnating varnish would be one that would penetrate readily into the deepest, tightest coil and remain there while

by some simple process it is converted into a permanently hardened material in the shortest possible time without injury to the turn insulation. Such an ideal material should not have a solvent which would evaporate during curing.

New substances have been developed which may achieve this goal in that they contain no volatile matter which must be expelled during application (the conventional varnishes contain about 50 per cent volatile solvent by weight) and in addition are converted to a solid mass uniformly throughout any thickness simply by heating at moderate temperatures without the aid of oxygen from the air and without the formation of volatile reaction products. The resulting products have exceptional heat, water, acid, and alkali resistance and good dielectric and mechanical properties.

**10.17. Cable Insulation.** Electric supply cables are insulated with rubber, varnished cambric, or paper, and the paper insulation may be of the solid, gas-filled, or oil-filled type.

The choice between rubber, varnished cambric, and solid impregnated paper insulation is generally based upon voltage, cost, and ease of handling during installation. Rubber is widely used at the lower voltages (below 5000 volts) and where its resistance to moisture and its flexibility are of special importance, or where labor skilled in wiping lead sleeves is unavailable. High-voltage rubber cables are made for ratings up to 15,000 volts, but varnished cambric and impregnated paper are generally preferred where voltage, temperature conditions, and cost are unfavorable to rubber. Lead-covered (to keep out moisture) impregnated paper insulation is cheaper than lead-covered varnished cambric and in many of the larger systems it is used extensively for all voltages. As voltage goes up, dielectric losses become more important, and since varnished cambric is somewhat poorer in this respect than impregnated paper, it rarely is used above 15,000 volts.

Figure 10.7 illustrates four types of cable construction. In each, the insulating material has been applied to the individual conductors and a series of coatings added to protect against moisture or mechanical injury or both. Because the conductors are round in the three-conductor cables shown, a filler has been used to fill out the circular cross-section of the cable. The "belt" serves both to bind the conductors and filler together and as part of the insulation to ground.

Approximately 85 per cent of service failures of solid-type paper-insulated cable are from causes not inherent in the insulation, i.e., mechanical injury to the cable, corrosion of lead sheath, splits due to high and uncontrolled internal load cycle pressures, or leaks in wiped joints and fittings. Solid-type paper and varnished cambric insulations

give no warning of these troubles. With gas-filled impregnated paper cable (Fig. 10.8) loss of pressure serves as a prompt indication. Pure, dry nitrogen gas at 10 to 15 lb per sq in. is distributed throughout the cable length. (With medium pressure gas-filled cable these values are 35 to 45 lb per sq in.) Because of the maintenance of uniform gas pressure, less insulation is required than for solid-type cable. It has

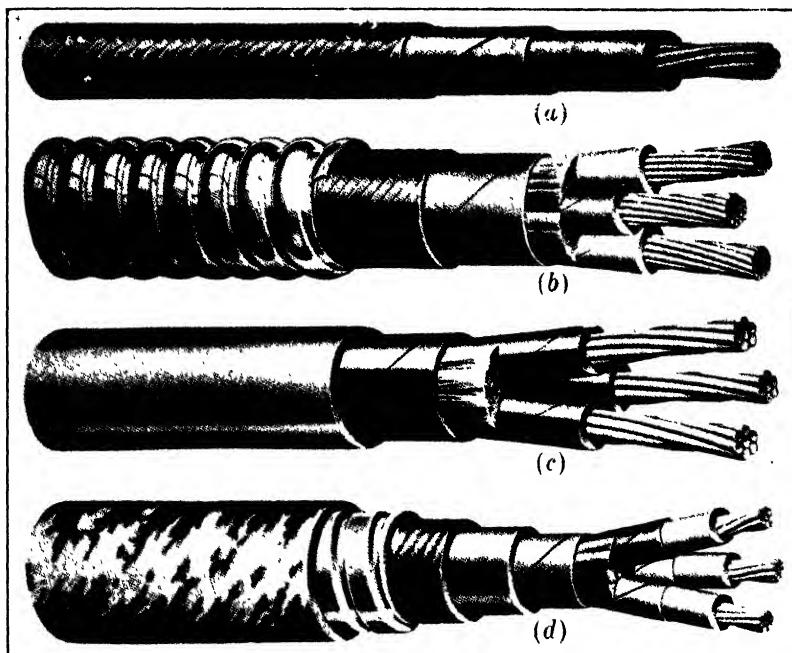


FIG. 10.7. Typical cable constructions.

- (a) Rubber-insulated cable with weatherproof braided finish (single conductor stranded).
- (b) Varnished-cambric-insulated cable with filler, belt, braided finish, and interlocked spiral steel armor (three conductor stranded).
- (c) Varnished-cambric-insulated cable with filler, belt, and lead sheath.
- (d) Parkway cable with rubber-insulated conductors belted, lead covered, protected by jute, interlocked armor, and jute over-all.

been possible to increase the dielectric strength still further by using gas pressures of 200 lb per sq in. in special casings, but suitable applications for this construction are very rare.

Oil-filled paper-insulated cables are used at 27 kv and above, and are used exclusively above 69 kv. Generally, the oil pressures range from

1 to 15 lb per sq in., the oil being distributed throughout the cable from reservoirs permanently connected to the cable. This type of cable was developed to overcome the voids caused by migration of the insulating compounds used in solid cable (such as plastic flow of compound away from sections of cable lying at the top of steep slopes). Instead of supplying the insulating oil through small tubes within the cable cross-section, one type of system has a steel casing around the paper-insulated conductors which is filled with insulating oil under pressure as high as 200 lb per sq in. Here again the system is better suited to very special applications than to general use.

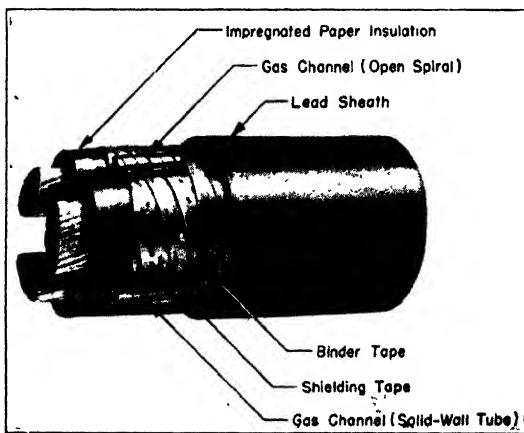


FIG. 10.8. Gas filled cable construction.

**10.18. Conclusion.** Even though the best of the available materials is applied in accordance with the best practice, service experience may still show insulation weaknesses if some factor of importance has not been considered in the design. New insulations, new applications, and new treatments, therefore, are best accepted only after satisfactory performance in accelerated tests simulating service conditions.

In considering design problems in the manufacture of electrical apparatus, a knowledge of existing insulating materials and their properties, as related to coil design, manufacturing, assembly and service requirements, is most desirable if progress is to continue. A consciousness of the importance of insulation to motor, coil, and cable life, and a constant effort to reduce costs of materials and methods by using the best engineering methods of approach, will result in improved quality and reduced apparatus costs.

## REVIEW QUESTIONS

1. (a) Name at least six criteria which might be used in various applications as the basis for selecting an insulating material. (b) Tell how each of the characteristics named might be measured in the laboratory.
2. (a) What are the limiting temperatures for each of the four insulation classes? (b) In what insulation class or classes is varnish? Mica? Cotton?
3. (a) What are the sources of drying oils? (b) Distinguish between a "short oil" and a "long oil."
4. (a) What is a "spirit varnish" and what are spirit varnishes used for? (b) What are the outstanding qualities of alkyd resin varnishes? Of Formvar?
5. (a) Discuss the relative advantages and disadvantages of white mica and amber mica, and tell where they are most often used. (b) List the advantages and disadvantages of glass fiber insulation for motors.
6. Distinguish between the three porcelain-making processes, and compare the qualities of the porcelain made by each.
7. (a) What are the compositions of steatite and Mycalex? (b) How can they be fabricated, and for what type of parts are they used?
8. (a) What harm may result if the air spaces in a coil are not filled with the insulating medium? (b) If varnish dipping does not give sufficient penetration, what measures might be taken to cause the coil to fill completely?
9. Name three types of cable insulation, and the kind of application in which each is most generally used.

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## CHAPTER XI

### PLASTICS AND THEIR MOLDING

By F. W. WARNER and W. S. LARSON

**11.1. Introduction.** In the broadest sense, a plastic is defined as any nonmetallic material which can be molded to shape. This definition has been narrowed, however (more or less by common consent), to include only a certain group of natural and synthetic resins and their compounds which can be molded, cast, extruded, or even used for coatings and films. Practically all of these resins are of an organic nature, composed of combinations of hydrogen, carbon, oxygen, and nitrogen.

Bituminous plastics were used industrially in the eighteenth century and pyroxylin, shellac, and casein plastics were developed in the nineteenth century. But the announcement by Dr. Backeland in 1909 of the development of phenol formaldehyde plastic really marks the beginning of the modern plastics industry. Since then research has developed many new plastics which have become commercially important.

**11.2. Classification of Plastics.** Plastics are most conveniently classified according to their origin as follows:

#### ORGANIC PLASTICS

##### *Synthetic Resins*

*Condensation Products*

- Phenol aldehydes
- Urea aldehydes
- Melamine aldehydes
- Aniline aldehydes
- Alkyds
- Polyamides

##### *Polymerization Plastics*

- Polyacrylates
- Polystyrene
- Polyvinyls
- Polyvinylidene halides
- Petroleum, coal tar, and pine pitch derivatives (cumarone indene, polyterpene hydrocarbon, Vinsol, etc.)

##### *Cellulose Derivatives*

- Cellulose nitrate
- Cellulose acetate
- Cellulose acetate butyrate

- Ethyl cellulose
- Regenerated cellulose
- Vulcanized fiber

##### *Natural Resins*

- Shellac
- Bitumen
- Rosin
- Copal

- Asphalt
- Amber
- Pitch

*Protein Substances*

Casein

Soybean

## INORGANIC PLASTICS

Refractory cold molded binders

Mycalex

Rubber and glass are not considered to be plastics. The dividing line is closely drawn in some instances, however, and plastics possessing both glasslike and rubberlike properties are available. Certain flexible resins of the polyvinyl group are sometimes classed as synthetic rubbers, and are used as rubber substitutes.

Plastics are also frequently classified into two groups, either thermoplastic or thermosetting, by their thermal characteristics. Those which undergo no chemical change in the molding operation may be softened again by heating to the temperature at which they originally became plastic, and are therefore termed *thermoplastic*. Since they become increasingly softer with increase in temperature, they are liable to permanent distortion under mechanical strain at relatively low temperatures (140 F), and have considerable cold flow. Those plastics which are permanently hardened by a fundamental chemical change in the molding operation are termed *thermosetting*. These materials, once molded, will distort under stress at approximately 250 F but will not become soft or fusible. Thermosetting materials will char and burn at high temperatures. A thermoplastic material might be considered analogous to paraffin or wax, whereas a thermosetting compound, by comparison, would be analogous to the clay used in making bricks.

**11.3. Constituents of a Molding Compound.** Molding compounds are made up of a resin or binder and one or more of the following components: fillers, plasticizers, dyes and pigments, and lubricants.

The *resin* is the principal component of the compound, gives the compound its name and classification, and imparts the primary properties to it. It is the cohesive and adhesive agent which provides rigidity and binds together the filler particles. The resin may be used by itself without the addition of a filler, as in cast phenolics; usually, however, it is combined with one or more of the other components.

The *filler* is usually an inert fibrous material which modifies the properties of the resin or imparts special properties to it. Fillers usually decrease the cost of the compound, decrease the shrinkage of the resin, and improve most physical properties, including the moldability of the compound. For example, a mixture of phenol formaldehyde resin with one or more of the following typical fillers results in a compound having the indicated characteristics.

<i>Filler</i>	<i>Characteristic</i>
Wood flour	General purpose, good appearance, low cost, good strength.
Cotton flock	Better impact strength, good appearance, good moldability.
Rag fibers	Highest impact strength.
Macerated cloth	Highest impact strength.
Asbestos fiber	High heat resistance, good dimensional stability, low coefficient of thermal expansion.
Mica	Good electrical insulation properties, low moisture absorption.
Graphite	Low friction.
Diatomaceous silica	Surface hardness, water and chemical resistance.

*Plasticizers* are added to the compound if the flow or softness of the compound must be regulated. The flow is usually governed to facilitate molding, but the plasticizer may affect the finished molded part. Compounds which contain a comparatively large amount of fugitive plasticizer may shrink and become brittle upon aging, owing to the loss of the plasticizer.

*Dyes* and *pigments* are added to impart color to the molded part. The natural color of many resins is a light brown, but they are frequently dyed black to provide a low cost uniform color which will not vary in shade.

*Lubricants* of wax or stearates are occasionally added to a molding compound to improve its molding qualities.

### PLASTIC COMPOUNDS

It would be well at this point to discuss more completely the most commonly used of the plastic materials listed on page 296. Each compound group, bearing the name of its resin, will be treated as a molding compound, i.e., a resin combined with the most suitable filler, plasticizer, dyes, and lubricant. Information concerning its manufacture, physical properties, applications, and available forms will be given.

**11.4. Phenol Aldehydes.** These materials are commonly known as phenolic molding compounds, or under the trade names of Bakelite, Durez, Resinox, Textolite, etc. The most common of this group, and

the most used of all plastics, is phenol formaldehyde,<sup>1</sup> the resin originally developed by Dr. Backeland in 1909.

Phenol formaldehyde compounds are the general purpose materials of the thermosetting plastics. They are comparatively hard, strong, and low in cost, can be molded to close tolerances and with a good finish, and have good all-around electrical, chemical, and thermal properties. By the proper selection of fillers, a phenol formaldehyde compound may

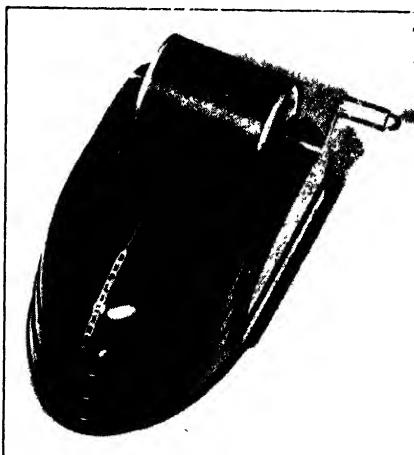


FIG. 11.1. A compression molded phenol formaldehyde housing.

be made to excel in impact strength, heat resistance, dimensional stability, electrical properties, or some other specific physical property. These compounds are limited in selection of colors to black, brown, green, blue, red, and other dark shades, and to combinations or mottles of them. They have low arc resistance and poor resistance to alkalies.

The phenolics are available as molding compounds and as resins for laminating and casting. The material is also available as finished laminated sheet, rod, and tube in a wide range of thicknesses and diameters. Typical applications are molded bases, covers (see Fig. 11.1), and operating arms for industrial control apparatus, bottle caps, hand-wheels and knobs, camera cases, and terminal boards. Laminated

<sup>1</sup> Phenol, synthesized from benzene and air or fractionated from coal tar, is reacted with formaldehyde (obtained from the distillation of hard wood or the oxidation of methanol) to produce a fusible and soluble resin. This resin may be dissolved in alcohol to form a varnish which is suitable for coatings or for laminating. If the resin is to be compounded, it is allowed to harden, after which it is pulverized, ground, and compounded with the desired filler, dye, plasticizer, and lubricant. This compound is then suitable for molding.

sheets with paper, cotton, or linen filler are widely used for punchings, mechanical applications such as gears, bearings, and cams, and structural applications such as panels, table tops, and rods.

**11.5. Urea Aldehydes.** Urea formaldehyde<sup>1</sup> is generally known under the trade names of Beetle and Plaskon. It was developed and put on the market in 1929 as the answer to the demand for a thermosetting material which could be made in the lighter colors, including white. It is used in the manufacture of such equipment as food scales, dishes, cosmetic containers, and gift boxes where white or an attractive color is a necessity.

The outstanding characteristic of urea formaldehyde plastics is the wide range of colors and pastel shades. Its mechanical properties slightly exceed those of an equivalent phenolic compound, and its resistance to electric arcs and tracking is greatly superior. Its cost is considerably higher, unless black or brown colors are satisfactory, in which case a less expensive grade 2 urea compound (wood flour filler) can be used. Thin sections of the lighter colors of urea formaldehyde are translucent, and because of this the material has found wide application in lighting units. Urea laminated sheets are generally used for decorative panels or table tops and offer a wide range of attractive inlaid designs and pastels. Urea resins are also used as hot or cold setting cements for bonding plywood and wooden assemblies.

**11.6. Melamine Aldehydes.** Melamine resins, principally melamine formaldehyde, are thermosetting and are synthesized from calcium carbide and nitrogen. They were first made available commercially in 1939. These resins were developed especially to fill the gap between phenolics and ureas with regard to electrical and physical properties. Melamine resins give a high dielectric strength and high arc resistance in combination with high heat resistance, low water absorption, and general inertness. This makes them particularly applicable to the molding of electrical parts, such as terminal boxes and boards, magnetos, and distributor heads, which are subject to adverse operating conditions. They are also ideal for tableware, buttons, lighting fixtures, etc., because they can be made in light colors and will withstand boiling water. The melamine resin is also used for laminating.

**11.7. Aniline Aldehydes.** This resin,<sup>2</sup> when compounded with cellulosic or mineral fillers, creates a molding compound outstanding for its electrical properties. It has high dielectric strength, low power factor

<sup>1</sup> Urea, synthesized from hydrogen, nitrogen, oxygen, and carbon, is treated with formaldehyde to form the resin. Alpha-cellulose, a pure white derivative of wood, is commonly used as a filler to complement the color and translucency of the resin.

<sup>2</sup> A condensation reaction between aniline and formaldehyde produces aniline formaldehyde resin.

and low loss factor, and retains good characteristics over a wide range of frequencies, despite adverse moisture conditions. It has good mechanical strength, is readily machined, and has exceptional oil and chemical resistance. It is available as molding compound or in laminated form, and is used most for insulation in radio and television parts. The compound is thermoplastic in nature but cannot be injection molded;<sup>1</sup> it may be compression molded and cooled in the mold.

**11.8. Polyamides.** The polyamides are a comparatively new group of plastics of nitrogenous structure of which Nylon is typical. They are of a crystalline nature and can be so processed as to orient the crystals axially, thus making the tensile strength of fibers comparable to steel. This property is so outstanding that the production of polyamides is largely confined to the extrusion of filaments, which are subsequently wound into thread and woven into hosiery, fabrics, or ropes, or which are used directly as brush bristles, sutures, etc.

**11.9. Alkyds.** These resins,<sup>2</sup> when properly modified, provide an excellent surface coating which has a durable glossy film and good adhesion and is readily applied. As such, they are widely used for automobile finishes, coated fabrics, ordnance paints, aircraft lacquers, and marine paints. They are not used for molding compounds.

**11.10. Polyacrylates.** The principal polyacrylate resin is polymethyl methacrylate, commercially known as Crystallite and Lucite. The family of acrylic and methacrylic resins are derivatives of acrylic acid and range from viscous liquids to hard thermoplastic solids. The softer resins are used as elastic adhesives and, in an aqueous dispersion, as a finish for cloth and leather. The monomers are used as casting resins for casting the sheet material used for transparent aircraft turrets and cockpit enclosures. The polymer, polymethyl methacrylate, is available as a molding compound.

The outstanding properties of the cast sheet and the molded forms of polymethyl methacrylate are their exceptional transparency and clarity, lightness, rigidity, and good weather resistance. The various forms in which it is available make possible a wide variety of uses, such as dentures, transparent enclosures, goggles and lenses, castings, and extruded tubing.

**11.11. Polystyrene.** Polystyrene resin,<sup>3</sup> in granular form, is used directly for injection molding or extrusion, usually without the addition of any plasticizers, fillers, or lubricants. The resin is a clear, hard, light

<sup>1</sup> Plastic molding methods are discussed in Secs. 11.18 through 11.24.

<sup>2</sup> Alkyd resins are esters of polyhydric alcohols (such as glycerol) and polyhydric acids.

<sup>3</sup> Styrene resins are made from ethyl chloride and benzene, which are derived from petroleum and coal, respectively.

thermoplastic without odor or taste. Parts made from polystyrene have a distinctive glasslike tinkle when dropped. The outstanding properties are its low specific gravity (1.07), its excellent resistance to inorganic chemicals, its low water absorption, its excellent dimensional stability, and its excellent electrical properties. These important properties have made polystyrene especially applicable to such items as battery boxes, chemical equipment and closures, radio and television insulation, refrigerator parts, lenses, and jewelry.

**11.12. Polyvinyls.** The polyvinyls include plastics which may be subdivided as polyvinyl alcohols, esters, acetals, and halides. In these classes are the following resins which are commercially important and of interest to the designer: vinyl acetate, vinyl chloride, copolymer of vinyl acetate and vinyl chloride, vinyl butyral, and vinylidene chloride.<sup>1</sup>

Various formulations of the vinyl resins present an exceptionally wide range of properties and applications. They exist as viscous liquids, or may be formulated into flexible or rigid solids. The property of flexibility at ordinary and subzero temperatures has led to the substitution of vinyl resins for rubber.

Polyvinyl acetate is available in various viscosities of the solid resin and in organic solvents and water emulsions. Mixed with a filler, it can be used for moldings and plastic woods. Its chief use, however, is as an adhesive and as a sizing or coating. As such it is used for food cartons and drinking cups, and for laminating cellophane.

Polyvinyl chloride is generally plasticized and finds wide use as flexible tubing, gaskets, and extruded wire covering. It is unaffected by oils and has an exceptionally good combination of chemical resistance, freedom from oxidation, and electrical properties. It may be obtained commercially as Koroseal.

The acetate-chloride vinyl copolymer combines the best properties of the individual resins into one. Compounds of low molecular weight are used for films and coatings; those with a higher molecular weight and a higher percentage of vinyl chloride are used for molding powders and sheet stock. Solutions of the resin in acetone are used in the manufacture of Vynon, an extruded filament used in the making of dental floss, woven fabrics, filter cloth, etc. Other solutions and coatings are used for lining food cans, waterproofing raincoats, and coating paper.

<sup>1</sup> Acetylene passed through acetic acid produces vinyl acetate or reacted with hydrogen chloride yields vinyl chloride. If the vinyl acetate and vinyl chloride are polymerized together, a copolymer vinyl results. Polyvinyl butyral is made by reacting polyvinyl alcohol with butyraldehyde. Vinylidene chloride is a product of the reaction of ethylene (from petroleum) and chlorine (from brine).

By highly plasticizing the vinyl copolymer resin, flexible and rubber-like, extruded and molded parts, sheet stock, and film may be made. This material is being used in clothing accessories such as wallets, belts, and suspenders, and in applications such as gaskets, covered wire, and shower curtains. Unplasticized sheet stock and molded parts are, on the other hand, noted for their dimensional stability and are used to fabricate charts, dials, and drafting and calculating instruments.

Polyvinyl butyral is a similar type of flexible sheeting which has found its main use as the interlayer of a safety glass sandwich. In that capacity it provides properties of elasticity, toughness, and good adhesiveness.

Vinylidene chloride is also known as Saran, and has a number of unusual properties. Chief of these is the crystalline structure of the compound which permits mechanical orientation of the crystals to increase the tensile strength of extruded strips and filaments. It also permits rapid solidifying of thick injection parts by crystallization instead of cooling. The material itself is tough and strong and has good chemical resistance and good electrical properties. It is thermoplastic but has a relatively high softening point of about 250 F. The molding compound may be plasticized to retain any degree of flexibility or rigidity of the molded or extruded part. Saran flexible tubing is an acceptable substitute for rubber in many applications, and extruded strips woven into fabric provide excellent seat and furniture coverings. Rigid Saran pipe has recently been introduced and has proved satisfactory as a replacement for iron and steel in certain uses.

**11.13. Petroleum, Coal Tar, and Pine Pitch Derivatives.** These derivatives, which include resins such as cumarone indene, polyterpene hydrocarbon, and Vinsol, are most suited to dilute or extend other plastics resins such as phenol formaldehyde. They also serve as bonding agents and coatings, and as adhesives and gums.

**11.14. Cellulose Derivatives.** Cellulose nitrate, the original Celluloid of white collar fame, is made<sup>1</sup> by the reaction of nitric acid and cotton linters. This plastic was first developed in 1869 to provide a substitute for ivory in billiard balls, thus making it the first true synthetic plastic. It is still widely used for the fabrication of fountain pens, toothbrush handles, spectacle frames, eyeshades, etc. The finished material is quite flammable and is difficult to mold; however, its advantages of toughness, water resistance, and a wide range of

<sup>1</sup> The compounds of the cellulose group are all derived from the digestion of cotton linters by an acid. The precipitated esters are then mixed with plasticizers, dyes, and solvents to produce molding and extrusion compounds.

attractive colors and mottles make it a favorite for many applications. Cellulose nitrate is available as lacquers and emulsions, as extruded rods and tubes, and as sheets 20 by 50 in. from 0.005 to 1 in. thick.

Cellulose acetate<sup>1</sup> overcomes the chief disadvantages of cellulose nitrate; it is nonflammable and molds very readily. It was first marketed as a molding compound in 1929 and did much to advance the practice of injection molding. Finished cellulose acetate products are tough, smooth finished, resilient, tasteless, and odorless. The material is available as transparent, translucent, or opaque, and in all colors and a variety of mottles and variations. It is not suitable for parts in contact with water and loses its mechanical strength at subzero temperatures. As a molding compound, its mechanical properties and its moldability and extrudability make it a favorite compound for small items which must take lots of abuse, such as flashlight cases, tool handles, goggles, combs, pencils, and kit boxes. Transparent sheets are being used as aircraft enclosures, specially formulated to decrease the sunburn suffered by pilots, and as a covering for wire screen to make a transparent shatterproof window. Cellulose acetate is especially adaptable to extrusion, and is available as rods, tubes, trim, and other standard shapes.

Cellulose acetate butyrate excels cellulose acetate in regard to dimensional stability and moisture resistance. Otherwise it is very similar as to manufacture, properties, and availability. Because of its special properties, this material fills applications such as radio dials, weatherstripping, hose nozzles, ammunition rollers, and window shades.

Ethyl cellulose<sup>2</sup> has recently found a ready welcome in the plastics picture because of its special properties of toughness at low temperatures, excellent dimensional stability, and improved chemical resistance. The principal applications are as lacquers and fabric dopes, parts drawn and fabricated from thin sheet, injection moldings, and extruded tubing. Special formulations possess rubberlike properties and are known as ethyl rubber.

Regenerated cellulose is more commonly known as Cellophane. It is prepared by extruding a viscose solution from a long narrow orifice through a coagulating and washing bath. The film is then rolled onto

<sup>1</sup> The material is made by treating cotton linters with acetic acid; the cellulose acetate formed is compounded with a plasticizer and is then pressed into large blocks or ground into molding powder.

<sup>2</sup> This plastic is made by treating cotton linters with sodium hydroxide and then ethylating the alkali cellulose.

mandrels and made into Cellophane sheet which is used principally for decorations and packaging.

Vulcanized fiber is made by treating a cellulose paper with zinc chloride, so as to laminate the layers and toughen the fibers. It is somewhat similar to a laminated product. It can be formed only to simple shapes, but can be readily machined, sawed, drilled, tapped, or punched. Fiber sheets are exceptionally strong and tough, especially on a strength-weight basis have good dielectric and arc resistance properties, and good chemical resistance.

**11.15. Natural Resins.** The natural resins include shellac, bitumen, rosin, asphalt, pitch, and copal. They are of a thermoplastic nature and were the first type of plastic to be used. Shellac is still an important natural resin, both as a coating and as a molding compound. Its principal application is the manufacture of phonograph records, although it has excellent electrical properties and is used in molded and laminated parts.

**11.16. Protein Substances.** Protein plastics were among the first to be discovered, but have seen little development. Casein plastic is pressed from precipitated milk curd to its desired shape and is then hardened in a formaldehyde bath. Practically all casein products are limited to simple shapes which can be fabricated from extruded rod or ribbon, such as buttons and buckles. The material has poor water resistance, but is otherwise hard and glossy, and available in all colors. Soybean plastic has been under development for some time, but is mainly limited to use as an extender for phenol formaldehyde resins. Both casein and soybean plastics are being extruded as filaments to produce a woollike thread.

**11.17. Inorganic Plastics.** The adoption of inorganic binders by the plastics industry is largely the result of the search for a material which will withstand high temperatures. Binders for cold molded refractory compositions include clay, silicates, and Portland cement. Combined with asbestos fillers, they are unaffected by heat as high as 1300 F. These materials can be formed into comparatively fine and delicate parts.

Mycalex is a glasslike plastic, employing a silicate binder which is mica filled. This material can be molded under high heat and pressure; when cooled it becomes hard and smooth finished, with good flexural strength and fair impact strength. It will withstand heat up to 550 F and has especially low power factor and dielectric loss. These properties make Mycalex especially applicable to radio and television parts which are subject to temperatures above the operating temperature of ordinary thermoplastics.

### MOLDING OF PLASTICS

To achieve a working knowledge of plastics and plastics parts design, it is necessary to fully visualize the methods and tools used in the manu-

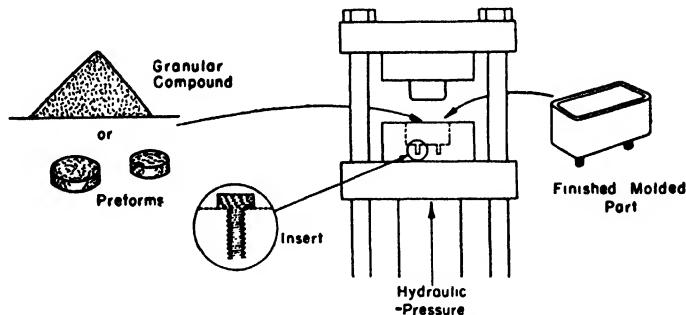


FIG. 11.2. Schematic sketch showing the steps in the hot compression molding of a small part containing two inserts.

facture of the molded part. To this end, the manufacturing processes hot compression molding, transfer molding, injection molding, extrusion,

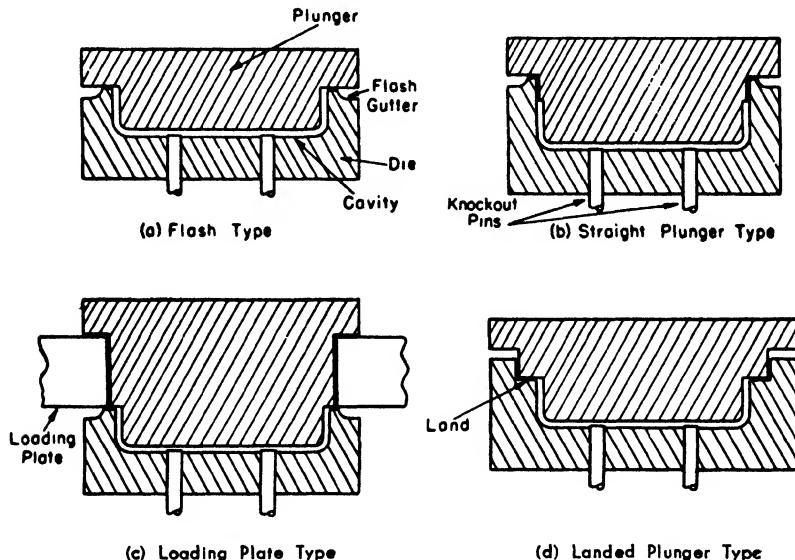


FIG. 11.3. Sketches illustrating the common designs of compression molds.

laminating, cold molding, and casting are discussed in this section. They are almost unique to plastics and give them much versatility.

**11.18. Hot Compression Molding.** Hot compression molding is the most commonly used method of shaping a thermosetting plastic to some desired form. The plastic compound, in the form of powder, granules, or preformed briquettes, is loaded into the heated mold cavity (see Fig. 11.2). As the mold closes under pressure, the compound becomes semifluid and fills the mold shape. The mold cavity and plunger are split at a convenient parting line so the finished part may be ejected.



FIG. 11.4. A large two-cavity compression mold.

All sections of the mold which form the part are of hardened steel and usually chrome plated to withstand the high pressure and abrasion. They are heated to a temperature of approximately 350 F, and pressures of 2000 to 10,000 lb per sq in. on the molding material are necessary to form the part. The material is then held in the mold until the resin has polymerized and become infusible. The length of time of this *cure* varies chiefly with the thickness of section and will usually take about 2 min for a section of  $\frac{1}{8}$  in., with increasingly longer cures for thicker sections. After the part has cured and become rigid, it can be ejected from the mold while still hot, and the cycle repeated.

The method of sealing off the compound and providing a cutoff at the line at which the cavity and the plunger come in contact leads to various designs, the most common of which are shown in Fig. 11.3. The proper type of cutoff is assigned to the mold by the mold designer.

The method of assembling the cavity and plunger into a frame is

shown in the sketch in Fig. 11.2, which illustrates the construction for a typical small single-cavity landed-plunger compression mold. Provisions are made for ejecting the molded part when the dies are separated. Fig. 11.4 is a photograph of a two-cavity compression mold.

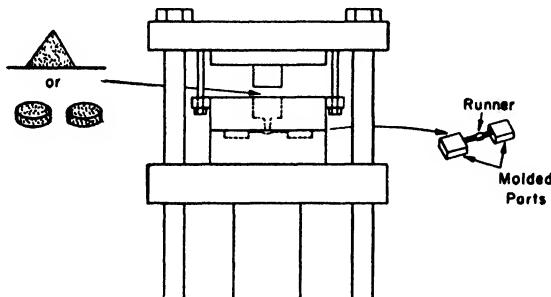


FIG. 11.5. Schematic sketch showing the steps in transfer molding.

**11.19. Transfer Molding.** Transfer molding employs the same materials and the same mold cavity as a compression mold. But it differs in this respect; in a compression mold, the molding compound is loaded directly into the molding space; thus, as the mold closes, the material is displaced under high pressure and with considerable turbulence. But in a transfer mold, the molding compound (usually thermo-

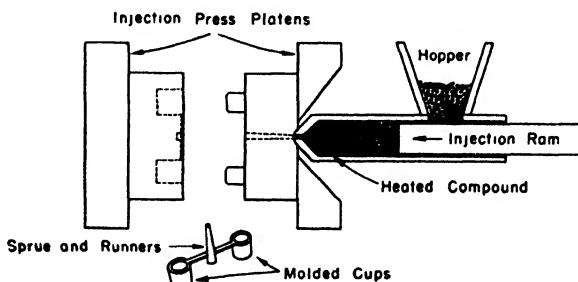


FIG. 11.6. Schematic sketch of the set-up for injection molding.

setting) is loaded into a separate pot or well; as the mold closes, a close fitting plunger causes the compound to flow from the well through a sprue and into the mold cavity (see Fig. 11.5). Thus, no appreciable pressure is exerted on the mold cavity until the cavity is completely filled and the fluid pressure is transmitted.

This absence of undue mold pressure is the outstanding advantage of transfer molding. It allows the use of molds with delicate mold sections and wedges and allows the use of fragile and weak inserts. Other advantages of the transfer mold are a better and faster heat transfer to the compound as it flows through the sprue, decreased cleaning through the elimination of build-up flash, and better molding tolerances.

**11.20. Injection Molding.** Injection molding has been applied principally to thermoplastic materials, but a recent improvement in the method of heating the compound has proved the process practical for thermosetting materials also. The process is very similar to die casting. The material enters a heating chamber independent of the mold; as it becomes plastic, a plunger operating at pressures up to 12 tons per sq in. forces the material through a nozzle into a cooled mold (for thermoplastics) or a hot mold (for thermosetting), Fig. 11.6. The part then solidifies or cures, respectively, until it is rigid enough to be ejected.

The transfer of the thermoplastic from a heating chamber to a cool mold eliminates the cycle of heating and cooling the mold, as would be necessary with an ordinary compression mold. The injection process thus lends itself to rapid automatic production of thermoplastic parts.

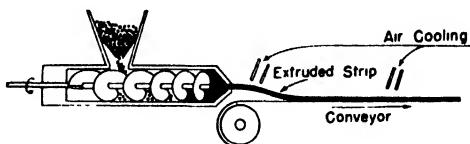


FIG. 11.7. Schematic sketch showing the extrusion of a plastic strip.

**11.21. Extrusion.** The extrusion of plastics is a means of molding a part of constant cross-section and continuous length. Material is heated to a plastic state in a cylinder; it is then forced from the chamber by a revolving screw through an orifice of the desired shape (see Fig. 11.7). As it leaves the orifice it is chilled by an air blast and is supported and removed by a long belt conveyor. As the solidified material reaches the end of the conveyor, it is wound on rolls or cut to convenient lengths. The final shape of the cross-section is affected by the operating conditions of the machine, and it is possible to vary the shape of the extrusion from any one die.

**11.22. Laminating.** A laminated material is one in which cloth or paper or other sheet material is impregnated with resin and bonded together under heat and pressure. It is a plastic in that it has a filler and a binder; it is of a unique form because the filler is not macerated,

ground, or shredded. Since the filler is in sheet form, laminated shapes are confined to flat sheets, tubes, rods, and very simple molded parts,

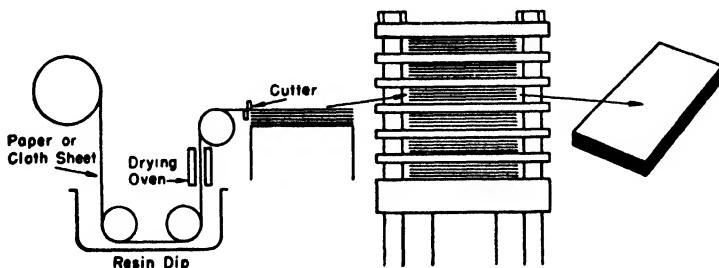


FIG. 11.8. Schematic sketch showing the steps in laminating sheets.

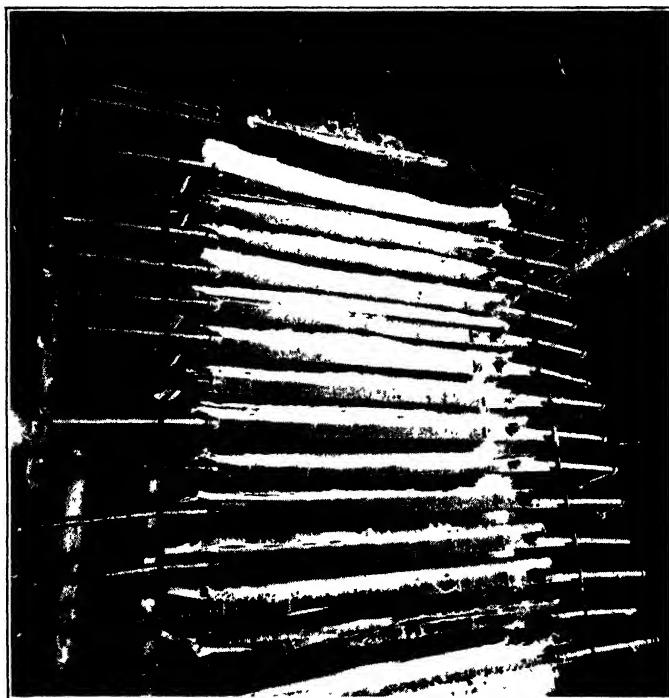


FIG. 11.9. Fifteen laminated canvas sheets ready for pressing in a hydraulic press.

such as radio speakers or army helmets. When forming sheets, the requisite weight for the desired thickness is stacked up, placed between two finished steel pans, and pressed between heated platens in a hydrau-

lic press (see Fig. 11.8 and 11.9). Tubes may be either molded or rolled. For molded tubes the paper or fabric is rolled on a steel mandrel of the desired diameter and then placed within a steel mold for the final processing (see Fig. 11.10). For rolled tubes the mandrel is heated, the paper or fabric is highly compressed by other heated rolls and the processing

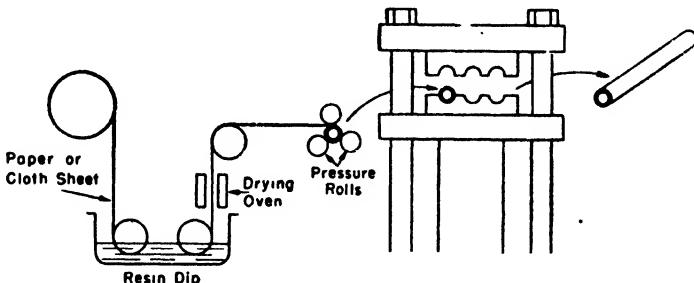


FIG. 11.10. Schematic sketch of the steps in laminating rods and tubes.

takes place as the mandrel is revolved, final curing being done by subsequent heat treatment. In the manufacture of rods, the paper or fabric is rolled on a mandrel of very small diameter which is withdrawn before the material is placed in the mold.

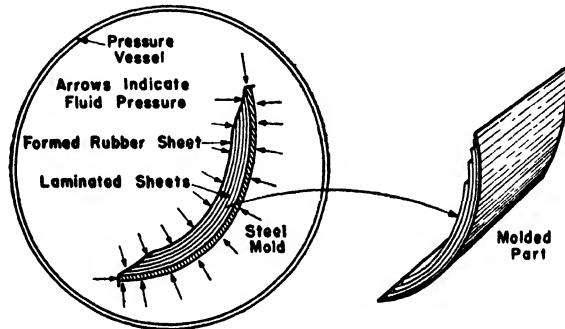


FIG. 11.11. Schematic sketch showing the method of low pressure laminating plastic parts.

Cotton cloth and paper laminates are most common, but laminates of asbestos paper and cloth and of glass fabric are also available. Heavy cloth laminates of cotton duck or linen are used for gear blanks, cams, and other industrial applications. Paper laminates are used principally for electrical insulation and punch stock material. Decorative laminates with figures or colored faces are available and are extensively used for table tops and wall facings. Vulcanized fiber is a form of laminate.

*Low Pressure Laminating.* Almost entirely different from the above process, but one which should be classified here, is the newly developed method of low pressure laminating. This process is being used for the laminating of large skin sections, such as airplane fuselages, parts of wing and tail assemblies, fairings, ducts, and numerous other large, thin section parts. Both resin impregnated plywood and cotton cloth are being used. The molding technique is such that the laminating material and the molding surface are sandwiched between two surfaces under a fluid pressure, as shown schematically in Fig. 11.11. Since the pressure is applied uniformly to both sides of the sandwich, the mold need have little rigidity, and can be built at comparatively low cost.

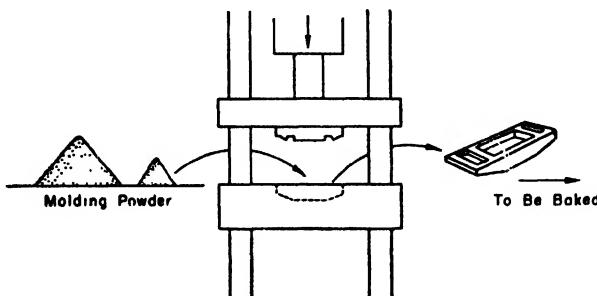


FIG. 11.12. Schematic sketch of cold molding process.

**11.23. Cold Molding.** Cold molding is a forming process in which a molding compound is pressed or cold formed to shape and then baked to achieve its final properties. Since the part is not cured under pressure and since cold molding compounds are rather coarse, the appearance of the finished part is not as pleasing as that of hot molded phenolics.

Molds for cold molding are usually of the straight plunger type. They are not equipped with heating channels and generally are single-cavity molds because of the poor flow of cold molding compounds. The abrasive action of the compound causes a high rate of mold wear. In the pressing operation, the mold cavity is filled with compound, usually of the nonrefractory type, and the mold is closed quickly and forcefully. The compound may then be further sized by opening and closing the press several times. The molded part is then removed from the cavity and placed on a tray, which is placed in an oven. The parts are baked for 1 to 3 days at temperatures to 425 F. In pressing refractory-type cold molded compounds, the parts are baked at higher temperatures to set the binder.

**11.24. Casting.** By a variation in the method of manufacture, some very clear viscous resins can be produced which will harden when

baked at a moderate temperature. Since no pressure is necessary to cause such a resin to fill a mold, very inexpensive and light molds may be used. This is the principal advantage of the use of cast plastics. Since they contain no filler, they have an unrivaled deep lustrous finish, available in any color or variegation.

Parts to be made must be of a fairly simple shape and have a broad dimensional tolerance. A steel mandrel is made to the outside shape of the part and is dipped into a lead bath until the film of lead can be

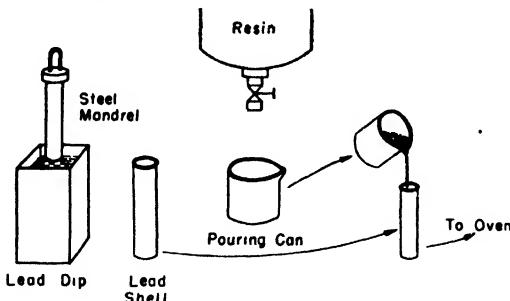


FIG. 11.13. Schematic sketch of casting process.

stripped from the mandrel and is rigid enough to serve as the mold for the casting. If the part is to be cored out, lead cores are made in a similar manner. The shells are then filled with resin and the resin is cured in an oven at 70 to 100 C for 2 to 6 days, depending on the thickness of section. These operations are shown schematically in Fig. 11.13. Finished parts such as small radio cabinets, chess and checker men, jewelry, sheets, rods, and tubes for machining and fabricating are made in this manner.

#### PART DESIGN

**11.25. Main Considerations.** The design of plastic parts involves three major considerations: (1) The selection of the proper material to give the desired properties, (2) the selection of a means of fabrication which is suitable and economical, and (3) the proper part design to enhance the material properties and to facilitate manufacture.

Since these considerations often involve the work of more than one department, there should be at all times close cooperation between all parties concerned. The engineer and draftsman should indicate all technical details and various mechanical and functional factors that must be considered. The artist lends his talents to creating a design and style which will be pleasing from the consumer's point of view and

will employ color in keeping with the trend of the times. The molder can select the plastic which will be most satisfactory and may suggest changes which will improve the part or make it more economical to produce.

There are many interrelated factors affecting the design, and the proper incorporation of these factors calls for a high degree of skill and experience. The use to be made of the product will require certain appearance and certain properties in the plastic from which it is to be made. Each plastic has a particular molding technique which will have an important bearing on the design. Additional factors are the size and shape of the product, and the estimated production.

**11.26. Design Sequence.** The normal steps in designing a molded plastic part should be in the following sequence:

- (1) The engineer and draftsman lay out fundamentals of the design.
- (2) The artist, using the fundamentals from the engineer and draftsman, designs the piece so as to make it attractive and symbolic of whatever the needs may be.
- (3) The engineer and draftsman interpret the artist's sketches by making accurate mechanical drawings of the designed part.
- (4) A perspective drawing should be made from the mechanical drawings.
- (5) The proposed design should be referred to the molder for his comments.
- (6) After the perspective drawing is found satisfactory, or corrections have been made, a model of the article should be machined or carved from any suitable material, such as wood, laminated or cast phenolic plastics, cellulose acetate plastics, clay, or metal. It is advisable to paint the model to represent the color of the molded part itself. Cellulose acetate can be used to advantage in constructing models, because of good machinability and the ease with which sections can be bonded by simple use of a solvent.
- (7) Models should be studied carefully by engineer, artist, molder, and production division to make certain that all are satisfied.
- (8) A single-cavity sample mold should be produced to make the article itself of the chosen plastic. This enables such important characteristics as shrinkage, assembly, and serviceability to be determined accurately before production tools are made.

While this step-by-step procedure may seem complicated, it is the simplest and surest way to arrive at a product which will be 100 per cent satisfactory. The time to call in the molder depends to a great extent upon the part being designed and the experience of the designers. For many industrial parts which are completely enclosed or hidden in

TABLE 11.1. COMPARISON OF PHYSICAL PROPERTIES OF THE COMMON PLASTIC MATERIALS

	Specific gravity	Tensile strength 1000 lb/sq in.	Notch impact strength Izod ft-lb/in. notch	Modulus of elasticity $10^{10}$ lb/sq in.	Thermal expansion $10^{-5}/^{\circ}\text{C}$	Max. operating temp. $^{\circ}\text{F}$	Dielectric constant $10^6$ cy	Dielectric strength VPM step by step 100 C	Power factor $10^6$ cy	Water absorption 24 hr, %
<b>Phenol formaldehyde:</b>										
Wood flour filled	1.22-1.48	7-12 2	0 2-0 4	0 7-1 0	2-6	250-265	60-100	4-4-5	0 014-0 041	0 25
Asbestos filled	1.6-2 1	5-8	0 2-0 4	1 0-1 5	4-7 5	250-265	60-75	4-5-8	0 035-0 1	0 2-0 7
Cotton flock filled	1.32-1.38	5-7	0 2-0 7	1 0-4 5	2-4 5	380-390	50-70	4-5-20	0 005-0 1	0 1-0 3
Rag filled	1.32-1.38	5-8	0 3-0 7	0 7-1 1	2-6	230-245	50-70	4-5-6	0 04-0 1	0 6-2 3
Urea formaldehyde	1.41-1.49	5-8.5	0 85-1 8	0 7-1.2	2-6	230-245	40-60	4-5-6	0 04-0 1	0 5-2 3
Melamine, cellulose filled	1.45-1.47	5-8	0 25	1 2-1.5	2-3	163-175	95-115	6-6-7 8	0 028-0 036	1-3
Aniline	1.2-1 25	8 10	0 3	0 45-0 6	5-6	210-225	180-200	..	3 6-3 8	0 006-0 008
<b>Cold Molded:</b>										
Nonrefractory Refractory	1.87-2 15	..	0 4	..	..	500	..	6	0 07	0 7-3
Hard Rubber	1 1-1 76	4 2-10	0 5-0 55	0 5	7	1300	..	..	..	0 6-15
Mycalex	2 9-3 4	5 2-7	0 5-0 7	0 4	0 5-1	600	340-360	3	0 003-0 008	0 2
Cast phenolic, unfilled	1.25	8 5-10	0 75-4	0 2-0 8	0 4	160-170	340-350	7 4	0 003-0 006	0 2
Cellulose nitrate	1 3-1 38	5-12	0 75-4	0 2-0 8	1 2-16	135-150	1200-300	6 3	0 02-0 05	0 4-0 6
Cellulose acetate	1 25-1 35	3 5-10	0 75-4	0 1-0 4	8-16	140-230	3 3-6 3	0 07-0 1	0 6-2	0 2-4 7
Cellulose	1 1-1 2	2 5-8	0 8-5 5	0 1-0 4	11-16	140-230	..	..	0 01-0 05	1 6-2 2
acetate butyrate	1 1.15-1 18	4-7	0 2-0 4	0 8-9	120-145	1470-510	2 7-3 5	0 014-0 03	0 4-0 6	0 2
Methacrylate	1 1.05	5-9	0 3-0 5	0 2-0 5	6-8	145-190	1440-540	2 5-2 7	0 002	0 2
Polystyrene	1.33	8-10	0 4-1 2	0 35-0 45	7	130-140	1370-400	3 2	0 013	0 2-0 3

<sup>1</sup> Dielectric strength at 25 C.

service, the second and fourth steps are omitted. For simple parts the sixth and seventh steps are omitted, and for low production items the eighth step is omitted.

Precautions should be taken to determine that the product is designed correctly in every detail before a mold is built. One cannot be too careful to avoid that overconfidence so often found in designers or customers who believe their designs on paper are perfect and, therefore, will not produce models or single-cavity molds but proceed with production molds immediately. Experience has proved that when molds are completed and the designer sees the actual part, he often finds that several changes must be made. With a model or a single-cavity sample mold, changes can be made quickly and with little expense. Changes in production molds are expensive and involve considerable danger of ruining the molds.

Almost any part can be molded at a price. However, the customer usually wants economical production. Definite restrictions are therefore imposed on the design of molded parts and the molds to produce them. These restrictions are constantly changing as new materials or new methods are found to eliminate or reduce them.

**11.27. Selection of the Proper Material.** Although the various classes of molding compounds have been discussed, it has been difficult to compare them on general terms. In selecting a material for a given application, certain desired physical properties will be the basis of selection. With this in mind, the most critical physical properties of the common plastic materials will be reviewed. A review of this nature is best given in a plastics handbook in which the various properties can be compared by actual test values; however, the comparisons shown in Table 11.1 will permit a general selection.

In using a table of values in the selection of a plastic material, it must be remembered that most compounds have a wide range of formulations, each of which produces a certain desired property at the sacrifice of other properties. Hence, do not assume that the upper values of several properties will hold for a given compound. The manufacturer of materials or the molder should be consulted in such a matter. The designer must further consider the operating conditions to which the plastics will be exposed. The physical properties and the operating characteristics of the part will be greatly affected by certain conditions, and allowances must be made for them.

**Mechanical Properties.** In a design involving calculation of mechanical stresses, the factors of fatigue, cold flow, and temperature, will affect the plastic. It is recommended that a safety factor of 4 over the short-time tensile strengths be used for parts to be subjected to one million

fatigue cycles, and a factor of 8 for sharply notched parts. Impact strengths will be similarly affected, and for 200,000 impacts, the strength may be only 30 per cent of the single blow impact strength. Cold flow is the permanent set caused by an applied load! Phenolics and ureas are least affected by cold flow but thermoplastics are rather susceptible. The tensile strength of phenolic materials decreases with an increase in temperature, while the impact strength is at its best between 100 and 160 C, and decreases rapidly above and below those temperatures. Tensile strengths of thermoplastics drop rapidly at very moderate temperatures such as 100 F. Impact strengths of thermoplastics decrease greatly at subzero temperatures.

*Other Properties.* Parts to be subjected to intense heat or fire will give the best service if made from flame-resistant material. Allowance must be made for heat, humidity, dust, and arcing in the design of electrical apparatus. Failure is frequently a result of a conducting track of dust, moisture, or an arced-over surface. Weathering will affect color, finish, and transparency of plastic parts; sunlight may fade or darken the color.

**11.28. Selection of an Economical Means of Fabrication.** This problem is rarely a matter of great question once the material has been decided upon. For any given material, there is usually one way which appears to be the best way. The difficult decisions arise, however, when the material selection is not unique, and when several different methods of fabrication, each with a different material, could be used. In general, the methods of molding compare as indicated in Table 11.2.

**11.29. Design of the Part.** The first principle to be remembered in designing molded parts is to design the part so that it can be removed easily from the mold. When this point is overlooked the molds are impractical for quantity production. Proper design and simplicity of construction in the molded part will result in simplicity in the design of the molds to be produced. The more complicated the molds, the more expensive will be the production costs. Do not assume from this, however, that complicated and intricate pieces cannot be produced. They can be, and are being, turned out regularly, but the mold costs and production costs are commensurate with their complexity. Regardless of the intricacy of a molded part, there are certain basic design factors which must be adhered to. These will now be discussed.

**11.30. Design for Molding.** It may be better to change a complicated design or a heavy section, such as a ball, to two or more simple moldings and assemble them (see Fig. 11.14).

Internal undercuts are difficult to mold, and it is usually better to split the part.

Avoid as much machining of the finished molded part as possible.

TABLE COMPARISON OF PLASTIC MOLDING METHOD:

Item	Cast	Hot Molded			Cold Molded	Laminated
		Compression	Injection	Transfer		
Forms	Sheets, rods, tubes, simple shapes subsequently machined to finished size	← Intricate shapes →	Rods, tubes, simple shapes subsequently machined to finished size	Extrusion	Moderately intricate shapes	Sheets, rods, tubes, subsequently machined to finished size, simple shapes of uniform section
Choice of materials	Few	Widest choice	Only thermoplastics	Only thermoplastics	Few	Fair choice
Finish	Very good	→ Good to very good →	Good	Good	Fair	Fair to very good
Metal inserts	No	Yes	Yes	No	Yes	Occasionally
Accuracy of dimension	Poor	Good	Best	Fair	Fair	Fair to good
Mold cavities	Single	Multiple	Multiple	Single die	Usually single	Multiple
Mold cost per cavity	Very low	High	Highest	Low	High	High
Production per cavity per unit time	1 casting	Medium	High	High	High	Low

Drilling, tapping, grinding, and machining of undercuts are frequently justified, but machined surfaces are more susceptible to wear and to absorption of moisture.

There should be no radii at corners on the parting line.

Consider the method of ejecting the piece from the mold, and incorporate in the design (and indicate) adequate surfaces or bosses for the knockout pins.

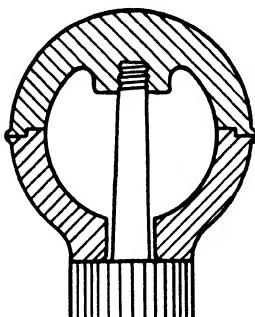


FIG. 11.14. Cross-section of a ball molded in two parts to eliminate heavy sections.

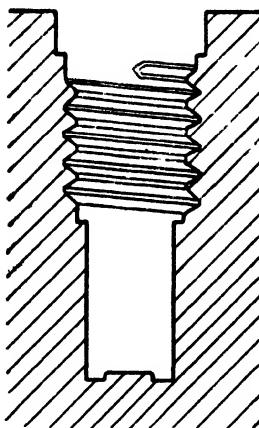


FIG. 11.15. Design of internal thread which provides for wear and rounding of thread plug.

**11.31. Designs which Facilitate Mold Construction.** Sharp corners, unless produced in a mold built up of sections or unless located at the cutoff (parting line), require extra and expensive die work. Deep barriers and fins likewise require difficult mold work.

Pins, wedges, and threaded plugs which must be removed from the mold during the molding cycle are likely to become nicked and rounded over. If possible, provide fillets and grooves in the molded part to allow ends of pins and wedges to become rounded over, or to allow shoulders on the tools to absorb abuse (Fig. 11.15).

Avoid molded parts which necessitate delicate mold sections.

**11.32. Dimensions, Tolerances, and Shrinkage.** Allowances are the intentional differences in dimension to take care of the fit; tolerances are the margins allowed for unintentional variations which occur during manufacture. Limits are the maximum and minimum dimensions which define the tolerance. Interference is a negative allowance. A basic dimension is the theoretical value of a dimension from which

variations are calculated. Tolerances are necessary on molded parts because of the unintentional variations in molds, molding technique, compound, and finishing.

For hot molded phenolic parts, specify these tolerances for fixed mold dimensions:

<i>Nominal Dimension (in.)</i>	<i>Preferable Tolerance (in.) (min)</i>	<i>Close Tolerance (in.) (min)</i>
$\frac{1}{2}$	$\pm 0.005$	$\pm 0.002$
1	$\pm 0.008$	$\pm 0.003$
2	$\pm 0.012$	$\pm 0.005$
4	$\pm 0.016$	$\pm 0.010$
6	$\pm 0.020$	$\pm 0.015$

Do not require close tolerances unless absolutely necessary; close tolerances require the best in tool construction and cause a higher percentage of rejects.

Cold molded parts will require about twice the preferable tolerance for hot molded pieces. Parts of urea require approximately the same tolerances as those shown for phenolic parts, but allowance must also be made for after-shrinkage of 6 to 8 mils per in. which takes place within a year.

Dimensions across the parting line must include an additional allowance for build-up of material. Allow  $\pm 0.010$  in. for wood-flour-filled compounds;  $\pm 0.015$  in. for large wood-flour-filled parts, small rag-filled parts, or parts from multiple-cavity molds; and  $\pm 0.025$  in. for large rag-filled parts. Transfer molded parts can be made with only a  $\pm 0.005$  in. allowance if necessary.

Allow  $\pm 0.003$  in. for warpage per linear in. of a flat surface, as measured by the sagitta of the arc.

Molded parts should not be used for the precision parts of sensitive instruments because all plastics show some after-shrinkage upon aging. The ureas and thermoplastics are worse in this respect than the phenolics. Their after-shrinkage is increased by hot dry service conditions. After-shrinkage and thermal expansion may also cause plastic parts to crack if they are rigidly fastened to dissimilar plastics or to a metal frame.

There should be close cooperation between the designer and the molder on the question of tolerances. The designer should give full details regarding important dimensions and desired tolerances and should completely specify the service to which the part is to be placed. The molder will indicate what tolerances can be met, and the cost of doing it, and will suggest possible modifications which will make for easier molding or reduced prices.

**11.33. Wall Thickness and Cross-Section.** In general, wall thicknesses should be limited to the following:

<i>Phenolic Parts</i>	<i>Translucent Urea Light Fixtures</i>
Minimum	0.025 in.
Small parts	$\frac{1}{16}$ in.
Average	$\frac{3}{32}$ in.
Large parts	$\frac{1}{4}$ in.
Practical maximum	1 in.

*Injection molded*

Preferable thickness 0.070 to 0.125 in.

Keep thickness of walls uniform, and avoid abrupt junctions of thick and thin sections. It is a good practice to hold variations in cross-section to less than 3 : 1. Core out heavy sections, especially for thermoplastics. Cross-sections with abrupt changes cause parts to crack after molding, from the strains set up by uneven cooling.

Thin walls require less material, less molding time, and are more economical up to the point where breakage and chipping occur. Sharp, delicate edges chip easily. Thin bosses and projections should be less than twice as long as they are thick. Thin walls may be reinforced with ribs. Thin uniform walls are especially important for urea molding because the ureas are sensitive to gas marks, poor knitting, and shrinkage cracks.

For covers and top surfaces, a dome construction is stronger than a flat construction.

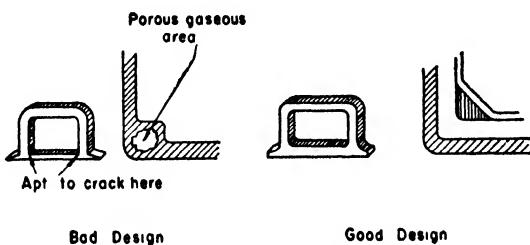


FIG. 11.16. Sketch illustrating good and bad design of a small part and a corner. Note that generous fillets are preferred and that abrupt changes in section should be avoided.

**11.34. Radii, Taper, Ribs, and Fillets.** Radii and fillets on molded parts reduce chipping, simplify machining of molds, assist flow of compound, improve appearance, and add strength. A radius of 0.010 in. is very small but sufficient to break a sharp corner; a 0.020 in. radius is slightly rounded and just noticeable; a 0.030 in. radius or larger is most beneficial. Fig. 11.16 illustrates the use of fillets to provide gradual changes in section.

Molded parts can be made with no taper if necessary, but they may show score marks on the sides. It is best to provide an average taper of one degree or 0.016 in. per in. (see Fig. 11.17). One-half degree is allowable. Three to five degrees should be provided for deep barriers or bosses. If no taper is allowed, state this definitely on the drawing; otherwise the molder will provide what he considers sufficient taper for proper molding.

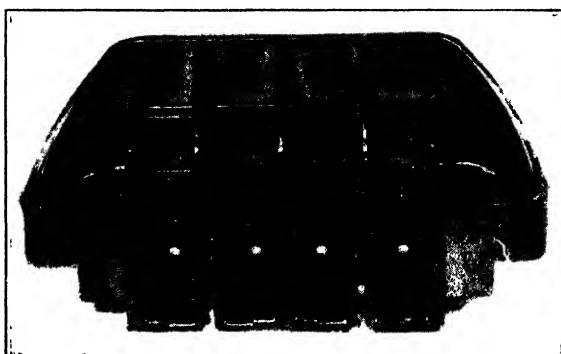


FIG. 11.17. A molded part for electrical control equipment. Note the generous use of fillets and tapers.

**11.35. Inserts.** Inserts for parts that are to be compression molded, especially if using rag-filled material, should be of brass or steel and sturdily designed to withstand molding pressure. The portion of the insert that is anchored in the compound should be no longer than twice its diameter for an insert supported at one end only; no more than four times its diameter for one supported at both ends. If the part is to be transfer molded, inserts such as brass strips, copper wires, or aluminum rods of almost any dimension can be successfully molded.

Adequate anchorage must be provided for inserts molded into a part. A medium or coarse diamond knurl is practically always sufficient; if it is to be subjected to great axial strain, grooves cut around the circumference of the insert will help. The slot in a screw head does not provide good anchorage against turning.

Specify whether the insert shoulder is to be below, above, or flush with the compound. If the insert is to be used as a mounting boss or electrical terminal, the shoulder should be above the level of the molded part (Fig. 11.18). In this way, the insert itself must absorb all of the axial tensile strain, and none of it will tend to pull the insert from the compound. If the insert is to hold a mating part snugly to the molded

part, or is to be used for assemblies, the shoulder of the insert should be flush with the surface (Fig. 11.19). This will allow the mating part to be drawn down firmly, but will not tend to pull the insert out. An insert that projects above the molded part requires a corresponding depression in the mold. Irregular depressions are difficult to make; therefore, design inserts with projecting portions round if possible.

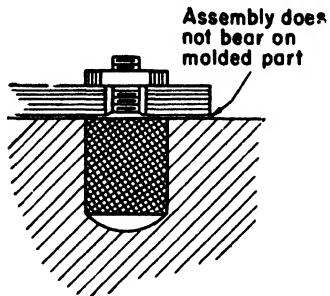


FIG. 11.18. Insert for electrical terminals.

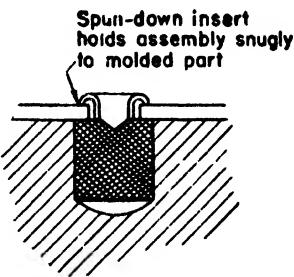


FIG. 11.19. Insert for assembling a mating part snugly to a molded part.

An adequate wall thickness must be allowed to cover the anchorage of the insert: for  $\frac{1}{4}$  in. diameter inserts, a  $\frac{3}{32}$  in. wall is minimum; for  $\frac{1}{2}$  in. diameter, a  $\frac{1}{8}$  in. wall is minimum; for over  $\frac{1}{2}$  in. diameter inserts, do not use less than  $\frac{1}{4}$  in. wall.

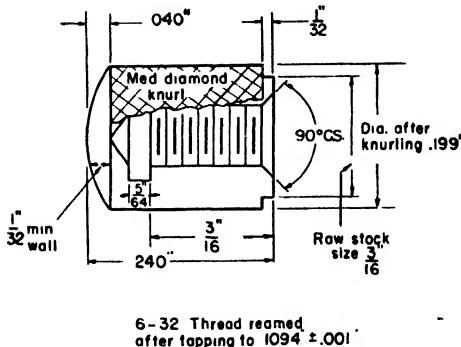


FIG. 11.20. A typical standard female insert.

Tolerance on the minor diameter of commercial female inserts may be as great as  $\pm 0.006$  in.; these inserts may shift on their supporting pins and so require excessive centerline tolerances. It is better practice to use inserts held to close tolerances such as  $\pm 0.001$  in. or  $\pm 0.002$  in.

A typical standard female insert is shown in Fig. 11.20. Note that

the knurl is terminated  $\frac{1}{32}$  in. from the face, that the end is curved, that the threads are undercut to provide full depth, and that the thread is slightly countersunk. These are all good features.

**11.36. Holes and Bosses.** Holes are formed by steel mold pins. As these pins are subject to breakage in bending they must not exceed certain limits of slenderness. The ratio of length to diameter should be limited to these values:

Type of Mold	Pin Support	Slenderness Ratio
Compression	{ One end	2 : 1
	{ Two ends	6 : 1
Transfer	{ One end	6 : 1
	{ Two ends	15 : 1

The slenderness of pins  $\frac{1}{16}$  in. or under, supported at one end only, should not exceed 1 : 1 in a compression mold.

Where a hole is to be molded with two butt pins, one pin should be at least 0.020 in. larger than the other to compensate for misalignment.

Molded holes for countersunk flat head screws should be slightly depressed and not butted at the base of the countersink.

Holes to be tapped after molding or holes for self-threading screws should be countersunk slightly.

Side or oblique holes are difficult to mold. It is frequently easier to drill such holes with the aid of drill jigs. Long holes of small diameter may be spotted and then drilled after molding.

**11.37. Threaded Parts.** Threads may be molded or tapped in almost all plastic materials. The American National form of thread is preferable. Other threads, such as a rolled thread for fuses and lighting fixtures and a round profile thread for closures and bottle tops, can be molded readily, but not tapped.

In general, threads above  $\frac{1}{4}$  in. in diameter should be molded, and smaller threads machine tapped. Use tapped inserts if maximum strength or frequent use is required. Do not mold threads smaller than size No. 8 or finer than 36 threads per inch; fine and shallow threads tend to fill with pure resin and are brittle. Molded threads are stronger and will hold their dimension better than tapped threads, which tend to swell where the resin has been cut. Do not retap a molded thread.

Molded threads should begin and end abruptly. A hole extending below a molded thread should be smaller than the root diameter of the thread, and tapered if possible. This facilitates removal of pin after molding. If the member forming the thread is stationary in the mold, provision must be made to unscrew the molded part.

Threads can be tapped as fine as 56 threads per inch. Do not tap threads over  $\frac{1}{4}$  in. in diameter. Mineral-filled compounds are brittle and are difficult to tap without chipping. Fabric-filled materials tap readily but the exposed cut surface will tend to swell when moisture is absorbed. Tapped threads can be held to a Class II fit (A. S. A.) on low moisture-absorbing materials on diameters under  $\frac{1}{4}$  in. When molded or drilled holes are to be tapped, allow an adequate cross-section, make the hole shallow but adequate (taps will clog on long holes), and tap through the hole if possible.

**11.38. Design for Appearance.** The best surface finish requires a highly polished, expensively finished mold; a fine filler and high resin content compound; provision to hide flow marks, rib and boss shadows, and knockout marks; and careful handling, wrapping, and special packing. Buffing produces a more highly polished surface but will not wear as well as a nonbuffed surface.

Large flat areas should be ribbed, stippled, or broken up into designs to hide flow marks. Knurled areas are decorative and provide a good grip.

Ribs, bosses, and inserts show through on translucent or transparent parts, and are usually very unsightly. Provision may be made to hide them with a surface rib, knurl, or other design.

The following colors are satisfactory in phenolics: black, brown, maroon, scarlet, red, dark blue, dark green, and dark mottles such as walnut and mahogany. Other colors are available but not too satisfactory.

Molded parts usually carry the molder's trademark, cavity numbers, and knockout pin marks. Surfaces on which to locate these should be shown on drawings.

**11.39. Printing, Painting, and Decorating.** Designs or intricate lettering can be applied to a part by photoengraving or by etching the mold. This produces a quite legible reproduction raised about 0.003 in. For higher letters, the mold is engraved. A common value is 0.010 in.; letters above 0.030 in. should include taper and a fillet at the base. Letters  $\frac{1}{8}$  in. high or less should not project over the adjacent surface more than 0.010 in.

Sharp metal stamps will print or roll onto a surface without heat. Deep relief branding is done with a heated die, and letters are 0.006 to 0.008 in. deep.

Letters to be filled with paint should have sharp edges, be 0.005 to 0.030 in. in width, half as deep as they are wide, and have bottom corners rounded. These letters are fairly expensive because they must be raised on the mold, which requires undercutting the entire mold surface.

**11.40. Aids to Finishing.** Parts can frequently be designed to facilitate the cleaning of flash and other finishing operations. Parting lines should fall on square edges or on crowned or ribbed surfaces which are readily accessible for filing. Flash forming around wedges, knockout pins, and plugs or name plates should be easy to clean.

Particular attention should be given to parting lines on decorative handles or knobs because such flash must be removed evenly, without marring the surface.

Inserts and electrical contacts which must be faced should project slightly above the compound.

**11.41. Design for Electrical Apparatus.** Sharp corners and points on inserts raise voltage gradient and lower dielectric strength in the compound.

If electric arcs between inserts are probable, provide a fiber or rubber insert or an air gap to prevent the arc from traveling on and carbonizing the plastic surface.

Phenolic materials will carbonize and form a conducting track when subjected to an arc. Cold molded compounds, fiber, rubber, thermoplastics, and urea are more arc-resistant.

**11.42. Assembly Devices.** Threaded inserts should be used for parts that may be frequently disassembled, for partial assemblies, for parts requiring adjustments, and for good strength. Self-threading screws should be used for economy, moderate strength, and infrequent disassembly. Drive screws are best for long holes and for permanent assembly.

Inserts with a spin-down collar and female threads provide rivet and screw connections and are very convenient. Rivet inserts may be spun down but should not be hammered down.

When considering assembly, all rigid mountings should be studied. Differences in the thermal expansion of metal and plastic, or in the aging of dissimilar plastics, may cause cracking.

Thermosetting or thermoplastic compounds may be cemented together to form a reliable and watertight seal. Thermosetting compounds should be bonded under pressure and baked. Thermoplastics can usually be cold joined with a solvent such as acetone.

**11.43. Conclusion.** The design of plastic parts is affected by improvement in the physical properties and performance of materials, and in their method of manufacture. For that reason, what may be an impractical or impossible design today might be readily produced by some improved material or method in the near future. In presenting this chapter, it is therefore recognized that the data on manufacturing methods and allowances, and the typical materials and their properties,

although seemingly adequate and fixed at present, may be modified or complemented by new developments in the near future which will permit extension of the applications and possibilities of plastics molding.

### REVIEW QUESTIONS

1. What characteristic is common to those plastics classed as thermoplastic? How do they differ from thermosetting plastics?
2. Name the various components which may make up a molding compound, and tell the function of each.
3. What characteristic properties do the following fillers impart to a molding compound: wood flour, rag fibers, asbestos, and mica?
4. Which of the plastic compounds is used the most? What other thermosetting compounds are used?
5. What is the difference between hot compression molding and transfer molding? For what type of work is the latter used?
6. What is the main advantage of injection molding for thermoplastic parts as compared with hot compression molding?
7. For what type of parts is extrusion usually used? Laminating? Explain the low-pressure method of laminating.
8. In what two ways does cold molding differ from hot compression molding? What kind of parts are made by cold molding?
9. What is the principal advantage of the casting method of molding plastic parts? What two design requirements are particularly important for molding parts by this method?
10. (a) Name two factors that influence the accuracy to which plastic parts can be molded. (b) What are good working tolerances for hot molded phenolics (1) on dimensions parallel to the line of molding pressure, (2) on dimensions perpendicular to the line of molding pressure?
11. The following suggestions are considered to be good practice in the design of molded plastic parts under most circumstances. State briefly the reasons which support each.
  - (a) Sharp corners should be avoided unless produced in a mold built up of sections, or unless located at the parting line.
  - (b) Walls should be as uniform as possible.
  - (c) The minimum wall thickness in phenolics is 0.025 in. and the maximum on large pieces is 1 in.
  - (d) Generous radii should be used to join changes in section.
  - (e) Inserts for compression molded parts should be flush or raised from the surface if they are used for fastenings.
  - (f) The slenderness of  $\frac{1}{16}$  in. diameter cantilever pins should not exceed 1 : 1. Larger pins may be 2 : 1.
  - (g) Threads greater than  $\frac{1}{4}$  in. in diameter should be molded, and smaller threads machine tapped.

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## PART II. PROCESSES

### CHAPTER XII

#### CASTING PROCESSES

**12.1. Introduction.** The casting process is the oldest, the most versatile, and the most flexible process for forming metals. Basically, it consists in introducing molten metal into a cavity or mold of the desired form and allowing the metal to solidify. There is practically no limit to the size, shape, and alloy of the castings that may be made. Castings regularly produced range from tiny dental inlays of rare metals to complicated steel castings exceeding 200 tons in weight. With proper technique and a design which incorporates a full appreciation of the foundryman's problems, almost any article may be cast. Numerous items could be mentioned which would be impossible to produce by any other method. It is, of course, not true that casting always represents the best solution to the production problem, but the possibilities of the casting method are of such significance that it should not be overlooked for either new or revised designs.

The type of molding material used has an important influence on the ease and cost of making the mold, the permanency of the mold, the speed of production, the rate of cooling of the molten metal, and the surface roughness, the dimensional tolerances, and the mechanical strength of the casting. Because of the relation of the molding material to the casting process, it is convenient in this chapter to divide the discussion between nonmetallic mold casting and metallic mold casting. In the former, sand mold casting will be considered first, and the discussion of other processes employing nonmetallic molds will follow.

#### SAND MOLD CASTING

**12.2. Molding.** In sand casting, the mold is made from bonded sand in such a way that liquid metal poured into it will, after solidification, retain the mold shape and can be separated from it. The correct mold form is obtained by using a wood or metal pattern of the desired part. The pattern is placed in a flask and molding sand is rammed around it. For casting some metals, a specially prepared layer of sand, called facing sand, is sifted over the face of the pattern and then the flask is filled with regular sand, called backing sand. At the completion

of the molding operation, the pattern is removed and then the mold is prepared for filling with the molten metal.

Patterns of simple design and with one or more flat surfaces may be made in one piece. Others may be split into two or more pieces to facilitate the molding operation. For large intricate castings, a pattern may have dozens of parts; but each part must be so placed in the flask

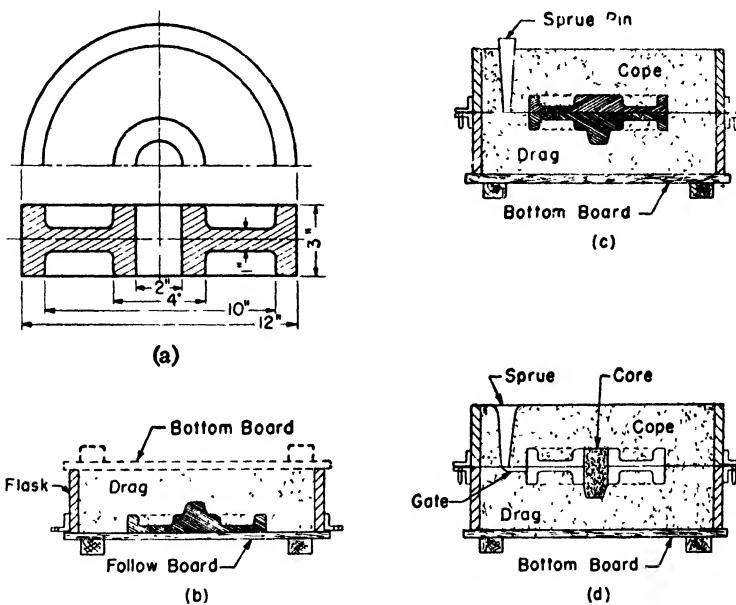


FIG. 12.1 Mold for a gear blank.

- (a) The machined blank.
- (b) The drag.
- (c) The cope.
- (d) The finished mold.

that it can be removed, after the sand has been rammed around it, without disturbing the impression it has left in the sand. At least two-part flasks are needed so the pattern may be removed. The portion of the mold in the lower flask is called the *drag*, and the upper portion is called the *cope*. Intermediate flasks known as *cheeks* are sometimes required for intricate pattern designs. An opening extending from the mold exterior into the mold cavity is provided so the molten metal can be poured in. Usually this opening is arranged so the metal cannot impinge on the bottom of the mold. The opening is called the *sprue*, and the place it enters the cavity is called the *gate*. Fig. 12.1 illustrates

an assembled mold for a gear blank, and the preparation of the drag and cope from a split pattern.

**12.3. Molding Equipment.** Molding operations may be classified as bench, floor, or pit molding. The main difference between them is the size and number of castings made and the equipment used.

Bench molding refers to the molding of small parts on a bench or table, each molder working alone. If the number of parts is small, all the operations may be done by hand. But if the foundry specializes in casting small parts, or if quantities are large, various types of molding machines may be employed. Machines are designed which will jolt the sand (for ramming purposes), squeeze the sand, turn over the flasks, vibrate the mold to facilitate the drawing operation, or draw the pattern. Other machines may perform some combination of these operations. In addition to this equipment, the molder has a variety of small hand tools (slicks, trowels, etc.) for performing any sand "sculpture" that may be required.

Work too big for bench or machine molding is molded on what are usually termed the side floor and the main floor. The work molded on the side floor can ordinarily be handled by two or three men without the use of mechanical handling equipment. Main floor molding requires the use of some type of lifting crane. The molding procedure is fundamentally the same as for the small bench work.

Some parts require a drag too large to roll over when filled with rammed sand, and for them, the drag portion is made in a hole or pit dug in the floor. A drag pattern is "bedded in" on regular molding sand. If there is a hollow space up inside of the drag pattern, the sand is rammed through openings in the pattern, either by building part of the pattern as ribs or by making it in sections which can be joined together as ramming proceeds. When the ramming of the drag is completed, the cope part of the flask is put on and rammed, then lifted off and placed on stools or standards and hand finished. Sometimes it is more convenient to ram up a relatively simple basic pattern in the floor pit, obtaining complicated details by placing large dry-sand sections (called *cores*) containing the final contours around the walls of the basic pattern impression. When much very large work is to be done, a concrete-lined pit is provided. Such a pit withstands the high fluid metal pressure better than a hole in the floor sand alone. Moreover, it keeps out moisture, facilitates the setting of cores, and provides a suitable anchorage for tie bars used to hold the top of the mold down so it can resist the pressure of the molten metal.

Besides the use of cores to simplify pit molding, cores are also used in all types of molding to obtain shapes containing holes, internal

cavities, undercuts, etc., that could not be molded along with the external contour of the pattern. Cores are made in separate forms and may be re-enforced to withstand the load that is imposed on them by the molten metal. They greatly simplify and reduce the cost of the molding operation, give greater accuracy for complicated cored-out sections, and make possible some castings that could not be molded otherwise.

All foundries do not use the same types of molding equipment. Choice depends on plant layout and the types of castings regularly produced. Sand conveyors, automatic sand sifters, pneumatic rammers, and sand-slinger ramming units are examples of power-driven equipment used in some floor and pit molding foundries. Because of the variety of equipment in use, it is to be expected that a mass production foundry and a smaller one engaged in job shop work might mold the same job in somewhat different fashion. Pattern alterations might therefore be required for work sent from one foundry to another in order to adapt the pattern to the molding methods in use. This point has not been generally appreciated in the past, and has resulted in some misunderstanding concerning the ability of foundries to cast certain jobs.

**12.4. Types of Molds.** The two types of sand most commonly used by the foundryman are referred to as *dry sand* and *green sand*. Both contain bonding agents such as fire clay, bentonite, and cereal or liquid binders, and a definite amount of moisture to promote cohesion. The dry sand mold is dried thoroughly by baking before it is closed and poured. The green sand mold is closed and poured without any preliminary drying operation. The type and quantity of sand grain and binder depend on which procedure is to be used. Binders are chosen for ability to burn out at molten metal temperatures so that molds and cores will collapse under compression and allow normal shrinkage to occur without damage to the casting.

Green sand molds have been found essential to the commercial manufacture of castings of intricate design because the green sand does not exert as much resistance to the normal contraction of the casting as does dry sand. This reduces the strains that must be supported by the solidifying metal, and thereby reduces the formation of hot tears or cracks. Dry sand molds have a firm mold face which is better able to withstand the metal weight and pouring erosion; and since their moisture content is to be removed anyhow, they do not have to be molded and poured the same day. The dry sand molds also require less care in molding, but they shrink a little in drying and are thus likely to be less true to form and size.

A modification of the green sand molding procedure is known as *skin drying*. In this procedure, the face of the mold, either plain or sprayed

with a special binding material, is dried by rapid heating with a gas torch. (Sometimes a short air-drying period may be used instead.) This gives a firm mold face as in a dry sand mold, with the more collapsible body of the green sand mold. Such molds have proved of great advantage in making some medium sized castings of intricate design.

**12.5. Types of Patterns.** The types of patterns used may be classified as (a) single loose patterns, (b) gated patterns, (c) match-plate patterns, (d) cope and drag patterns, and (e) special pattern equipment.

*Single Loose Patterns.* This is the simplest type of pattern, and it is used only for very limited production or for very large castings. The pattern may be split to facilitate molding, but it contains no gates, sprues, or risers (reservoirs for surplus molten metal), and the cope and drag must be made together since the pattern is not located with respect to the flask. The time required by the molder to cut gates and risers by hand increases the cost of producing castings from these patterns, and may cause a variation in the quality of the castings. For these reasons, small castings in even moderate quantities are often produced from other patterns.

*Gated Patterns.* Some time is saved in the foundry by having the gates formed by pieces attached to the pattern. The location and size of these gates should be left to the judgment of the foundry. Single gated patterns are used for comparatively small quantity production.

*Match-Plate Patterns.* Rapid production is facilitated by mounting the drag half of a pattern on one side of a wood or metal plate and the cope half directly opposite on the reverse side. This plate is attached to the drag flask and used like a follow board when ramming the drag; the cope sand is rammed against the reverse side. Finally the match-plate pattern is removed, leaving a cope and drag that match perfectly at the parting line. The gates are generally made by the pattern at the same time.

The match plate itself need not be flat so long as it is of uniform thickness in the direction normal to the parting of the mold. This feature permits patterns with an irregular parting line (e.g., handwheels or propellers) to be handled with comparative ease.

Although the match-plate pattern has a high first cost, this is more than compensated by the reduced labor cost per piece in large quantity production.

*Cope and Drag Patterns.* Separate cope and drag patterns facilitate rapid production on medium to large castings because one molder or group of molders may ram up the cope while another molder or group works on the drag.

*Special Pattern Equipment.* Special patterns may be used for some castings where the quantity to be made is low and further orders are not expected. Two of these are sweep patterns and skeleton patterns. Sweep patterns are made to the cross-section of the mold, and the mold is made by sweeping them through the length of the desired part. Skeleton patterns are made of the most inexpensive construction, usually of open type, which will permit the molder to make the mold. He may use clay to fill in spaces on the pattern and give it a continuous face. Patterns of this type should be considered only after consultation with both the patternmaker and the foundryman. Their use always increases the foundry cost but this may be offset by the saving in pattern cost.

**12.6. Wood Versus Metal Patterns.** Various factors to be considered in determining whether a pattern is to be made of wood or metal are cost, size, durability, production, and obsolescence.

**COST.** Wood, being cheaper, is most used.

**SIZE.** Beyond a certain size, all patterns are made of wood.

**DURABILITY.** Wood patterns are easily warped by moisture and in handling may become roughened, torn, and even broken. Wooden patterns are often metal lined in those places subject to most wear and tear.

**PRODUCTION.** If the size is not too large, high productivity jobs should always be made of metal.

**OBSOLESCENCE.** Where pattern changes due to redesign are likely to occur, the patterns should be made of wood.

The patternmaker should choose the type of pattern and its construction. When the foundryman and the patternmaker are not in the same organization, it would be well to consult the foundryman on the methods of molding and the pattern construction which will best suit the job. Frequently changes in construction which may even increase the pattern cost will make possible significant savings in the foundry. Or, with a different design, a lower cost pattern causing somewhat increased foundry costs may actually prove the least expensive in terms of the over-all cost of the finished casting.

**12.7. Pattern Design.** Although it is sometimes necessary for the designer to design the patterns for a casting, it is more frequently the responsibility of the patternmaker to make the pattern from which the part can be cast "to the drawing." Some of the points relating to the design of patterns which have an influence on the design of the casting are mentioned below.

**Parting Lines.** Since the flasks used to make each section of the mold are most conveniently parted in one plane, the parting line on the

pattern should be on the same plane, if the casting can be so designed. This makes for economical pattern and molding costs with all types of pattern equipment, although where production match-plate equipment is used, adherence to this rule need not be quite so rigid. Fig. 12.2 illustrates two parts — as designed originally, and new designs to facilitate parting.

*Locating Points.* When the finished casting is to be laid out for machining operations, it is advisable to facilitate checking in the pattern shop, foundry, or machine shop by indicating on the drawing the position on the pattern for locating reference points. Such points should be

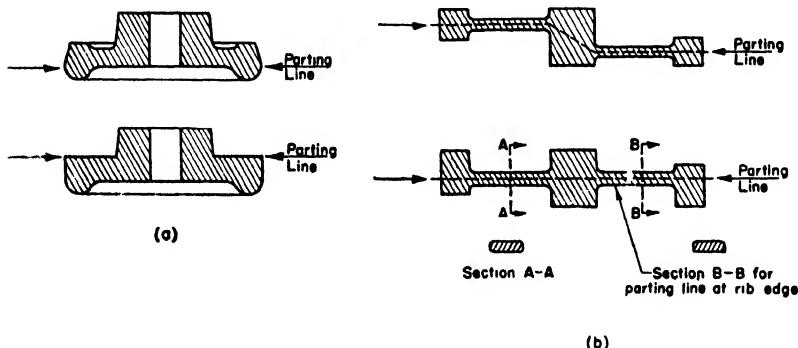


FIG. 12.2. Redesigns which facilitate parting.

- (a) Lower design eliminates need for overhanging sand in cope.
- (b) Lower design of four-spoke crank gives straight parting line either at centerline of the arm (for section AA) or at the bottom of the arm (for section BB).

located so they will not be influenced by core shift or shift of the cope or the drag. That is, they should be placed on the same side of the parting line, and as far apart as the size of the casting will permit. Surfaces which have no finish allowances and are held to close tolerances usually serve this purpose very well.

It is also helpful on some castings to include lugs, bosses, or other surfaces for locating and supporting the part during the machining operations. Sometimes such jig spots will serve no other purpose and may be removed after machining is completed.

*Core Prints.* Core prints are sections put on the pattern to provide adequate location and anchorage of cores. The length of the core print should generally equal the core diameter or width, but for prints that must balance overhanging cores, or overhanging sections of drop cores, a much larger print may be required. Cores which have a diameter or width greater than their length can frequently be molded in green sand,

by proper pattern design, thus eliminating the cost of a separate, dried-sand core, and no print need be put on the pattern.

*Pattern Allowances.* The dimensions on the pattern differ from those on the drawing to allow for metal shrinkage, distortion, core shift, draft, and machine finish. Such allowances are made by the patternmaker and serve the following purposes:

Shrinkage allowances provide for the contraction in dimensions of the solidified casting as it cools from its freezing temperature to room temperature. This shrinkage ranges from  $\frac{1}{32}$  to about  $\frac{5}{8}$  in. per ft depending on the metal; and it is added to the pattern so the finished casting will be of the correct size. The design of the casting, the restraint offered by projecting sections, and the resistance of the mold to the contraction all limit the shrinkage which will occur in different sections, and thus complicate the patternmaker's problem of allowing for proper shrinkage. The tolerances on the size should therefore be at least half the maximum shrinkage allowance for the metal involved.

In some designs, it is necessary to add an allowance for distortion and core shift. A casting of "U" section, for example, should have the open ends converged enough that the shrinkage of the closed end will straighten the side members of the finished casting. The initial convergence is the distortion allowance. An example of a core shift allowance is the metal (called *backing*) added to a thin section to assure necessary thickness, in accordance with the expected tolerances on core placement.

All surfaces perpendicular to the parting plane are given a slight taper or *draft* to permit easy removal of the pattern without excessive loosening (makes mold larger), or tearing of the mold walls. The amount of draft usually allowed depends on the shape and size of the castings, the molding method, and the type of sand used. For general work, the amount of draft is not less than  $\frac{1}{16}$  in. per ft. This may be added to or subtracted from the drawing dimensions, according to its effect on the subsequent use of the casting. When no instructions are given, the patternmaker will ordinarily divide the draft, i.e., add one-half and subtract one-half, if the wall thickness permits.

Metal is also allowed for cleaning up surfaces to be finished by machining. This allowance must be sufficient for the machinist to take a cut which removes normal surface indentations and gets below the surface scale as well as the hard metal directly beneath. The location of the machined surface in the mold (drag is preferred — add extra for surfaces in cope), the metal, and the machining setup to be used also affect the amount.

For convenience in using patterns in the foundry, all wooden patterns

and core boxes are painted in accordance with a standard practice.<sup>1</sup> Finished surfaces, unfinished surfaces, seats for loose pattern pieces, core prints, and stop-offs are all designated with a distinctive color or colors.

**12.8. Design of Castings.** The ideal casting from the standpoint of the foundry would be of such shape that (a) all its parts could be molded and poured easily, (b) it could be fed from one riser at the highest point in the mold, and (c) the solidification would proceed regularly from the lowest point to the feeding head, as in an inverted cone. Seldom can the designer achieve this ideal because of the limits placed on the shape and metal distribution by the functions of the casting. It is recognized, however, that an understanding of the mechanism of solidification and the effects caused by faulty design should permit the designer to introduce modifications which enable the foundryman to handle any remaining difficulties by reasonable foundry procedure — thus producing sound economical castings to the advantage of both groups. This section is included to help promote an understanding of the importance of design to the production of sound castings. It is thus hoped to make the engineer conscious of the benefits that he can obtain by seeking the foundryman's suggestions for improving castability of the design before it is so far completed that desirable modifications cannot be incorporated.

The three main characteristics of solidifying metal which affect the soundness of a casting are the melting temperature, the volumetric contraction or shrinkage, and the strength in the temperature zone just below freezing. The higher the melting temperature, the higher the temperature at which the metal must be poured, and the greater the rate of cooling in the mold. The high rate of cooling makes it difficult to pour thin sections without having them freeze before they are completely filled out. Increased handling difficulties may also result when the pouring temperature is high. Large shrinkage makes it necessary to use large risers (also called headers or feeders) which will freeze later than the casting and will supply liquid metal to compensate for the loss in volume as the solid metal cools. The strength of the metal at a temperature just below freezing is important because the cores and the mold may offer considerable resistance to the contraction, and the internal strain which occurs shortly after freezing may cause a fracture if the strength is low.

Of the commercial metals cast in sand, steel probably offers the great-

<sup>1</sup> The reader is referred to U. S. Department of Commerce Commercial Standard DS-19-30 or American Recommended Practice B45.1-1932 of the Procedure of the American Standards Association for a discussion of this practice.

est difficulty. It has a high melting point, a high volumetric shrinkage, and, in common with other metals, a low strength at temperatures near the freezing point. The technique for casting steel has therefore been more exacting, in general, than for other metals, so it is particularly important that steel castings be properly designed. The remainder of this section will deal with design precepts which have been found expedient in designing steel castings. It should be recognized that the same principles will, in general, apply also to casting of other metals, although the degree of importance may be less. It should also be recognized that although a pattern for a steel casting is properly designed, it may not prove suitable for casting other metals without changing the gates, risers, and dimensions, and vice versa.

*Defects in Castings.* Sand castings are subject to certain defects which, in a well designed casting, are controllable by proper foundry technique, but are not wholly predictable or preventable. Most defects are hidden below the surface of the casting and so cannot be detected by visual inspection. The designer must therefore either design to avoid or minimize such defects, or accept certain shortcomings and make allowances for them. The defects associated with the foundry practice include internal blowholes, slag inclusions, and centerline weakness (the junction of grains grown from opposite mold faces). The defects more directly attributable to poor design are *hot tears* and *shrinkage cavities*.

*Hot Tears.* As discussed above, hot tears are caused by excessive internal stress on the metal when its temperature is slightly below the freezing point. This stress may be caused by large temperature gradients in the casting, by a design which opposes contraction, or by stresses set up through the resistance of the mold to contraction.

Hot tears can be prevented by eliminating sections which remain hot after others have cooled considerably and by eliminating the stresses, particularly the concentrated stresses.

Hot sections, or hot spots as they are sometimes called, may be formed by a difference in section thickness. The thinner section freezes first and is contracting even before the heavier section has solidified. The heavy section thus becomes a hot section. Occurrence of hot sections of this type can be reduced to a minimum by *designing all sections of a casting with uniform thickness*.

Even with uniform thicknesses, hot spots will still be formed at the junction of two or more sections because the ratio of cooling surface area to metal volume is less than for the straight sections. These junctions therefore cause a thermal gradient and accompanying stress. Since they also provide conditions for stress concentration, they are quite favorable to the formation of hot tears. The stress concentration

can be reduced by using a fillet at sharp corners of junctions and by making all changes in sections as gradual as possible. These two measures in turn will reduce the formation of hot tears.

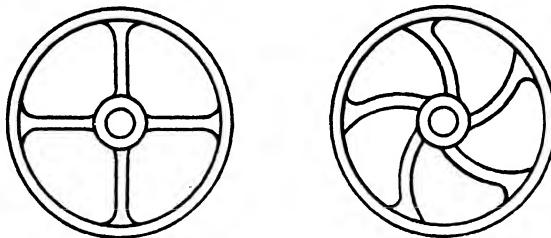


FIG. 12.3. Design of a large wheel with curved (right) instead of straight (left) spokes to allow the rim to contract without introducing excessive internal stresses.

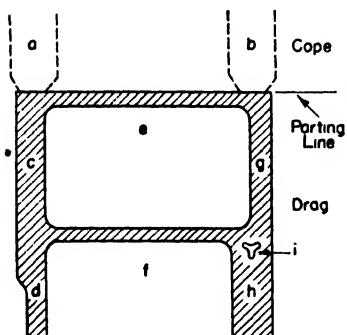
In some intricate castings it is not possible to avoid hot spots and thermal gradients. With these designs, the foundryman may reduce the stresses by use of mold relieving technique, but it is frequently

possible for the designer to produce a better job by designing the casting in two or three parts, which are later assembled by welding or bolting.

Another way of reducing these major stresses in an enclosed cast structure is to use members that are slightly curved or waved. Connecting members are usually chosen for this purpose, and they are distorted as the heavier sections cool, thus reducing the internal stresses without tearing. Fig. 12.3 is an example of a design which incorporates this principle.

FIG. 12.4. Cross-section of casting showing the formation of a shrinkage cavity. Sections *e* and *f*, being thin, solidify quickly and are easily fed by the headers on each side. The heavy section, *h*, being below the lighter section, *g*, and separated by *g* from the riser, cannot be fed effectively and consequently shrinkage cavity *i* is produced. Design of these sections as at *c* and *d* would eliminate this effect.

they increase the possibility of casting leaks under pressure, and they promote the fatigue failure of castings subject to vibration. Although



*Contraction Cavities or Shrinkage Cavities.* These cavities are caused by lack of sufficient metal to care for metal contraction at the time the casting solidifies. They are found in sections that must be fed through smaller sections, as illustrated in Fig. 12.4. Such cavities are objectionable because they reduce the static strength of the section,

it is quite true that these cavities could be avoided by using a riser to feed molten metal to every hot spot, it is not always convenient for the foundryman to go to the expense of such a procedure. In addition, the foundryman may mold the casting in a different manner than the designer anticipated, thus making some hot spots inaccessible. It is therefore much sounder practice to design the casting with the supposition that none of the junctions can be fed from outside reservoirs.

Briggs, Gezelius, and Donaldson<sup>1</sup> have made a study of various junctions in steel castings. Five basic sections, L, T, V, X, and Y, with fillets and, occasionally, cores of various sizes were poured without a riser so the junction had to be fed from the arms. The results of these studies are summarized in Fig. 12.5, which shows the best design studied, and an alternate which is considered satisfactory. In the L and V shapes, the junctions having radii which make the corner slightly narrower than the arms seemed most satisfactory. In the X section, it was found that a considerable offset of the arms gave the smallest shrink cavity. For T and X sections, the radius at the sharp corners should not be large. Best results in T, Y, and X are obtained by using a central core.

These general proportions of sections should be instructive to the designer, but when applying them he should consider the possible effect of joining these sections to other members of an integral casting.

*Directional Solidification.* The term *directional solidification* refers to the solidification which proceeds along a cast member in the direction

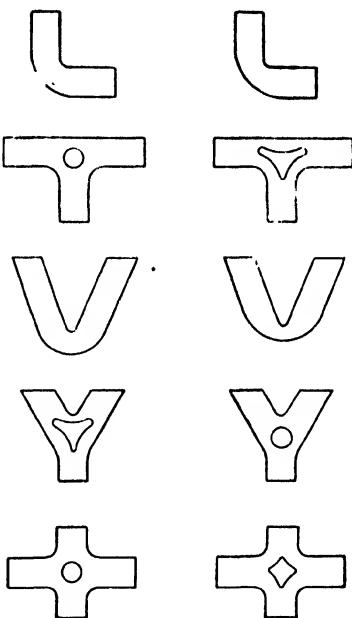


FIG. 12.5. Designs of junctions which minimize formation of shrinkage cavities and cooling stresses. The sections at the left are considered best and most practical, those on the right are satisfactory. (From "Steel Castings Handbook," Steel Founders Soc. Am., 1941; originally from C. W. Briggs, R. A. Gezelius, and A. D. Donaldson, "Steel Casting Design for the Engineer and Foundryman," Preprint 38-28 A.F.A.)

<sup>1</sup> "Steel Casting Design for the Engineer and the Foundryman," by C. W. Briggs, R. A. Gezelius, and A. R. Donaldson, *J. Am. Soc. Naval Engrs.*, May 1938; also *Trans. Am. Foundrymen's Assoc.*, Vol. XLVI, 1938, p. 605.

of the hotter metal. Solidification of this type differs from *progressive solidification* which is the freezing of the metal from the mold-metal interface toward the center of the cavity. By controlling the direction of solidification so the casting freezes toward liquid metal feed heads which can supply voids caused by shrinkage, it is possible to produce sound castings. This can be accomplished by the proper placement of feeding heads, by using tapered sections (narrowest section most remote from feeder), and by proper use of chills. Chills are metal sections inserted in the mold to remove an extra amount of heat from the molten metal. External chills remain in the sand and do not become a part

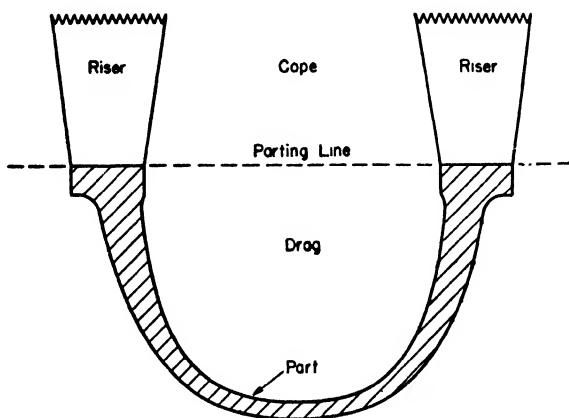


FIG. 12.6. Cross-section of simple shell with two bosses showing use of tapered section to control directional solidification. If the casting must have a uniform wall thickness, the extra padding may be removed by machining.

of the casting. Internal chills are rarely melted by the molten metal, so usually retain their form although they are a part of the casting. Their use is discouraged because porosity or other internal weakness is often caused by them, especially when extreme care is not used regarding their cleanliness.

The use of tapered sections to control the direction of solidification is illustrated in Fig. 12.6. This method seems a direct contradiction of the recommendation that uniform sections be employed. Actually the designer cannot be sure of the method of molding and may apply a taper in the reversed direction. If he provides a uniform section, however, the foundryman can usually obtain the correct solidification. In castings where every advantage must be taken of the principle of directional solidification, the designer and the foundryman should study the

problem together. Frequently the use of a small model will facilitate the discussion and will help to visualize both the original design and any changes that may be suggested.

*Effect of Mass on Mechanical Properties.* The immediate result of the slower cooling which occurs with heavy as compared with light cast sections is a greater variation in mechanical properties over the cross-section. The center of the heavy section is more apt to have large grain size, inclusions or voids, and low density, and possibly, in steel, carbon segregation. All these characteristics promote a reduction in strength and ductility, in the heavier as compared with the lighter section in the as-cast condition. The variation is somewhat reduced in nonferrous metal sections that have been annealed, and can be practically eliminated in steel castings where grain refinement may be obtained through heat treatment.

The mechanical properties to be accepted in the metal of a casting are covered by purchasing specifications when strength is a requirement. To determine whether a given casting meets specifications, it is customary to test sample metal specimens taken either from coupons cast on the part itself, or from test coupons cast separately but from the same melt. In general, these coupons can be favorably placed for casting, and the feeding of the metal to them is better than to the rest of the casting. As a result, the strength and ductility of the test bars are apt to be somewhat superior to the properties which are obtained in various sections of the casting.

*Section Thickness for Various Cast Metals.* The best practice is to use wall thicknesses that can be poured without danger of incomplete filling out, and that will provide the necessary strength or weight. In general, section thicknesses should be proportioned to the area to be run and should be in proper proportion to the adjoining sections, particularly those above and below it as the job is poured.

**STEEL.** Where the over-all dimensions are not too great, steel castings with wall thicknesses as low as  $\frac{1}{4}$  in. are poured regularly in many steel foundries. In special cases, it is possible to pour wall thicknesses of  $\frac{3}{16}$  in. or a little less, depending on the design of the casting. For best properties, such as are necessary in pressure castings and highly stressed castings, the minimum thicknesses are at least double these figures.

**GRAY IRON.** Gray iron castings are made in a wide variety of section thicknesses. The white irons may become gray if poured into heavy sections, whereas gray irons may become white if poured into very thin sections. Soft gray cast iron may be poured into  $\frac{1}{8}$  in. sections and retain its grayness. Cast iron with a tensile strength in a 1 in. section of

over 40,000 lb per-sq in. may be hard and white at the corners and edges if poured in sections thinner than  $\frac{1}{4}$  in.

**MALLEABLE IRON.** Malleable iron is cast commonly in sections  $\frac{1}{8}$  in. and less in thickness although the average section is approximately  $\frac{1}{4}$  in. Castings of this material may be cast satisfactorily up to several inches in thickness, depending on other dimensions and the design of the part, by proper adjustment of the composition. They may range from a fraction of a pound to more than 1000 lb, although the greater proportion of malleable iron goes into castings under 25 lb in weight.

**NONFERROUS.** The minimum thickness for nonferrous castings varies with the alloy, size and intricacy of the casting, pressure requirements, etc. Castings poured at excessive temperatures, to run extremely thin sections, generally are deficient in physical characteristics and should be avoided. With brass and bronze,  $\frac{3}{32}$  in. is considered the minimum satisfactory metal section. With aluminum alloys,  $\frac{1}{8}$  in. sections have been cast satisfactorily, although a minimum thickness of  $\frac{3}{16}$  in. is preferable.

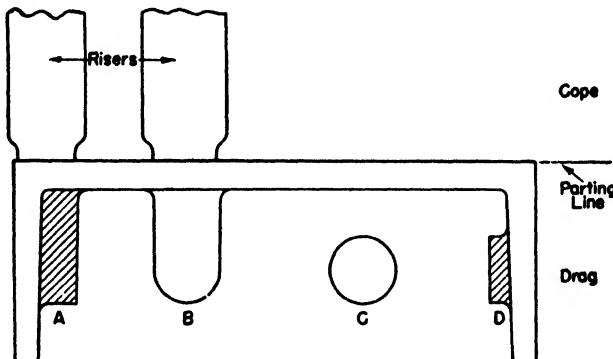


FIG. 12.7. Bosses should be designed with a heavy section leading to the feeding source, as at A and B. In C and D no such provision has been made, and either an internal or an external chill would be required. In addition, bosses C and D would not draw with the pattern, but would have to be made with loose pieces or a core.

**Bosses.** Bosses are often located on a wall of a casting and should be so designed that a heavy section of metal leads to the feeder. This is illustrated in Fig. 12.7, as with A and B. No such provision is made for bosses C and D, and internal or external chills would be required to prevent a shrinkage cavity in them. These two bosses are more expensive to mold because they have to be made by use of either a core or loose pieces on the pattern as they cannot be drawn with the pattern as can the bosses A and B.

**Ribs.** Ribs are used primarily as stiffeners and re-enforcing members. They not only increase the tensile strength of the casting, but if properly designed and located in difficult castings, serve to check the possibility of hot tears, or cracks during solidification. Their function, in this respect, is to solidify earlier than the section which they adjoin and act as a bond to prevent cracking, and to act as conductors of heat to promote cooling of the section involved.

The relationship of rib section to main section should be such as to permit as far as possible a uniformly graded metal section. Where feasible, heavy rib intersections should be staggered (as in Fig. 12.8) to avoid local increased section thickness and the consequent possibility of internal shrinkage. Fig. 12.9 shows three types of rib design for aluminum alloy castings. In certain castings, the tendencies of large

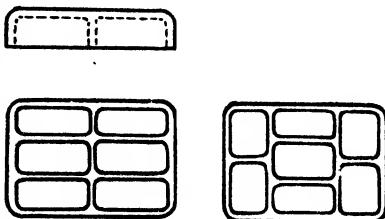


FIG. 12.8. Design of base plate (left) modified by staggering ribs (as at right) to eliminate X junctions. Staggered ribs also reduce distortion caused by shrinkage.

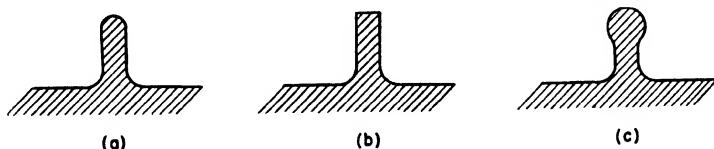


FIG. 12.9. Three types of rib design for aluminum alloy castings: (a) poor because of high fiber stress at extreme outer edge, (b) satisfactory, (c) preferred.

flat areas to distort when cooling from casting temperatures may be eliminated by properly designed and located ribs.

Ribs located perpendicular to L sections should be cored out at the corner section to avoid the hot spot which would occur there (Fig. 12.10).

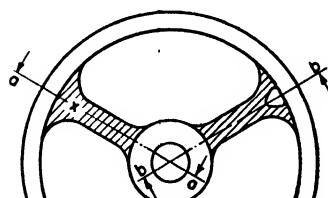


FIG. 12.10. Elimination of shrink cavity, X, by coring out junctions of spoke and rim of pulley or gear blank as in spoke b-b.

**Fillets.** Properly proportioned fillets at all intersections materially increase the strength and soundness of castings, and reduce costs from unavoidable foundry scrap due to shrinkage cracks and erosion of sand at sharp intersections.

Sizes of fillets depend upon (a) metal used, (b) shape and thickness of the wall section, and (c) size of the casting.

The use of fillets in various sections was discussed above. Fig. 12.11 illustrates an iron casting incorporating good fillet design.

*Deep Pockets.* Deep pockets and small recesses that complicate drawing the pattern or lifting the cope should be avoided, if possible, and when used, they should be made as large as permissible, and tapered.

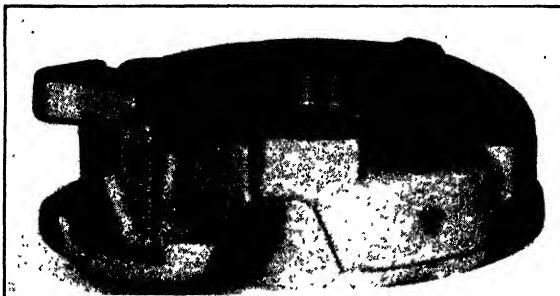


FIG. 12.11. Cast iron end shield and bearing bracket illustrating generous use of fillets.

*Cored Holes.* In steel castings, small holes which require finished surfaces usually are drilled and not cored, although it is often desirable and sometimes necessary to core out small holes, which are drilled later, to avoid shrinkage cavities in the bosses. Small and large holes, on which no machine finish is required, usually are cored, providing the tolerance is at least  $\frac{1}{16}$  in. on the diameter. Large holes which require machined surfaces frequently are cored and subsequently bored to dimension.

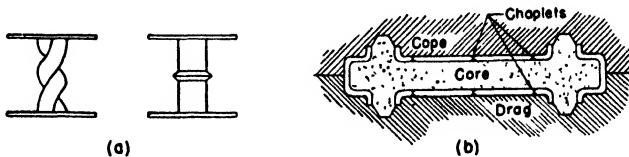


FIG. 12.12. (a) Two designs of chaplets and (b) an illustration of their use on an internal core.

Where the design calls for the use of cores, provision must be made for the anchorage of the cores to avoid shifting or lifting (floating) of them. Wherever possible, they should be supported and anchored by core prints, but metal supports can be used, as an alternative. One type of metal support is a chaplet. It is used particularly with internal cores as illustrated in Fig. 12.12. Chaplets are to be avoided when possible as they constitute a potential point of weakness in the casting, and in

steel castings such affected sections must often be chipped out and the hole welded up.

Besides special support, internal cores also require provision for venting. Sometimes the design will permit them to be vented through their core prints, but extra prints may be required if the original ones designed are not adequate. These extra prints may also be required to facilitate removal of the core sand from the finished casting. The difficulties introduced by internal cores both in making the core and in handling it in the foundry make it advisable to avoid their use when another design will serve as well. It is also good practice to avoid the use of dry sand cores in green sand molds when green sand cores can serve or a change in form can eliminate need for a core.

Where there is the possibility of assembling a core upside down or backwards, a locating or indexing lug or form should be used so the core can only be placed in the correct manner. If several cores are needed, it is desirable to use duplicates when convenient, thus saving core boxes.

*Inserts.* Metal inserts are occasionally cast into sand castings when properties not possessed by the cast metal are needed. A good knurl or groove should be used in the insert to provide the required mechanical bond. Sufficient metal should also be allowed around the insert so as to avoid foundry difficulties. Inserts will act as chills, and this action should be considered in their design.

**12.9. Finishing and Inspection.** After the casting has cooled, it is removed from the mold by either manual or mechanical means. The cores are cleaned out, and risers, gates, fins, and other excess metal are removed by flame cutting, arc cutting, sawing, chipping, or by hammering with a sledge. The rough surfaces are then dressed up with a grinding wheel. High velocity washing may be used to remove adhering sand, and when the surface scale is objectionable it may be removed by sand or grit blasting. Barrel finishing may also be employed on small pieces. Some parts, particularly large castings, are stress-relief annealed before blasting or washing.

The cost of cleaning a casting depends on the simplicity of the design, on the method of molding, and on the metal. Oftentimes on large, complicated castings, small cores surrounded by heavy sections of metal have a tendency to fuse on the metal, forming a substance as hard as glass and almost impossible to remove. Although this effect can be overcome to a certain extent by the use of cores made from silica sand or zircon, these materials are not generally used, and so small cores surrounded by heavy metal should be avoided. Steel requires the largest risers because of the greater shrinkage and so, in general, requires more expense for cleaning excess metal. The weight of metal in a finished cast-

ing ranges from 40 to 80 per cent of the metal poured. This ratio is spoken of as the *yield*. It is lower for steels than for iron and other metals, and is lower for pressure-tight castings than for structural work.

Depending on the application of the casting, sections of it or test bars cast at the same time may be tested for mechanical properties, and if many castings are to be made, sample castings may be tested to destruction to determine freedom from imperfections. The trend of employing castings for relatively high temperature, high pressure service has also introduced radiographic methods for nondestructive examination of the interior of castings. Very short wavelength gamma rays or x-rays are passed through the casting. This radiation will be absorbed by any defects to a lesser extent than in the adjacent sound metal. A photographic film is placed in the emergent beam, and the regions of greater exposure indicate images of the internal defects. Stereoscopic means may be used to locate the depth of such defects. When they are objectionable, if the casting is of steel or one of a few other alloys, the metal surface and the defect may be chipped out and refilled by welding. Unfortunately, many metals, including malleable iron, gray cast iron, and heat treated aluminum alloys, cannot be repaired in this way without special techniques and possibly a serious loss in strength.

Machining, grinding, and quenching cracks at or near the surface of castings may be detected by either a magnetic or a fluorescent test method. The former is used for magnetic materials and consists in magnetizing the casting in a magnetic field and then coating it with iron filings or immersing it in a bath containing iron filings. If a crack is present, tiny magnetic poles will be formed on each side of it and the filings will adhere there. The fluorescent method is a new development for nonmagnetic materials. In it the part to be examined is immersed in an oil bath under pressure, which forces oil into the surface cracks. The excess oil is washed off and any cracks present can be detected under ultraviolet light as it causes the retained oil to fluoresce. When castings must be pressure tight, a nondestructive pressure test may also be employed. All the parts or openings are blocked off and the casting is filled with water, air, oil, or kerosene under pressure and maintained for some specified length of time, while the casting is studied for leaks that might develop. Testing a casting for cracks, defects, or porosity by air is apt to be hazardous, particularly if the pressure applied is very great. Great care is exercised to vent all pockets where air might be trapped.

**12.10. Conclusion.** The casting process is subject to a great number of variables. Some of them are (*a*) the great proportion of handwork involved, (*b*) the control of molten alloy composition and temperature,

(c) the type of equipment available, and (d) the kind and quality of molding material available. The foundryman attempts to control these factors and their mutual effect on shapes, sizes, sections, junctions, ribs, bosses, fillets, etc., to produce sound castings at low costs.

In the absence of the designer's understanding of the influence of the design on casting quality and casting costs, the foundryman is often called upon to produce exceptionally tricky and intricate castings. Sometimes in desperation or perhaps because of pride of workmanship, he may endeavor to cast such a design. A clever foundryman can, and often does, produce exceptionally difficult castings. But his chances of duplicating this feat would be greatly increased if *he and the designer would cooperate in considering modifications in design which would lead to simplification of the casting procedure and would minimize the hazards involved.*

From the suggestions already made for the design of castings, it is apparent that cooperation can result in quality maintenance and improvement. It is not as readily apparent that cost and appearance can also be controlled by mutual consideration of the problem. The proportion of the cost of the foundry operation which is attributable to finishing may range from 25 to 75 per cent of the total. This cost may be limited by designs in which (a) the parting line junctions are minimized and simplified, thus minimizing irregularities in casting contour, dimensional variations, poor appearance, and risk of defective castings; (b) risers can be located with respect to variations in metal sections so they introduce as little distortion as possible during cooling, and are accessible for removal; (c) the surfaces to have the best finish are in the drag portion of the mold, and the in-gate, molding materials, and risers are all located so as to give best appearance; (d) the junctions for assembly or weldments are strategically located.

These foundry techniques can only be applied by the foundryman if he is fortified with a knowledge of the use of the casting, its control sections, vital dimensions, and important surfaces. Such information also facilitates the construction of the pattern. Sometimes the pattern-maker can suggest ways to avoid the necessity for patterns "to the other hand," i.e., right and left patterns. He can often influence the dimensional accuracy of the final casting by proper use of the directional properties of wood. And of course his choice of materials (hard or soft wood, metal, etc.) affects the life of the pattern and thereby the quality of castings produced from it. Other modifications may make possible the elimination of core boxes, incorporation of pattern draft into the design, and elimination of ever-troublesome chaplets and chills.

In presenting the section on the design of sand castings, it is therefore

emphasized that the ideas suggested, although adequate for many design problems, *cannot and should not take the place of a cooperative study of the design by the foundryman and the designer*, and adoption of those changes which prove to mutual advantage.

### CASTING IN OTHER NONMETALLIC MOLDS

**12.11. Plaster of Paris Castings.** Like a sand mold, the plaster mold produces only one casting and is then destroyed. The advantage of the plaster mold is therefore found in the quality of the product rather than in added permanence of the mold. The castings made by this method have superior surface finish, better dimensional accuracy, finer detail, and a more solid structure than sand castings, although at a higher piece price before machining.

Plaster has been used as a molding material and for cores for several centuries, but the above advantages were not realized commercially until developments during the past 6 years. The plaster used is composed of gypsum plaster (calcined calcium sulphate), fibrous strengthener (magnesium silicate), and a small percentage of impurities (salts and hydrochloric acid) to accelerate the setting of the mixture. Water per cent in excess of the amount required to set the plaster is added. This plaster mix is poured around the pattern, and when it reaches the semi-set state, the pattern is removed, forming the mold cavity. A match plate pattern is used, permitting the cope and drag to be made separately. The match plate is fastened to the snap flask (flask with hinge) and may contain as many as 20 different or identical individual patterns along with gates, risers, etc. These individual patterns are made from metal and may be added or removed at will, thus making substitution economical.

After the mold impressions are completed, the flask with match plate is removed, and the cope and drag halves are baked separately. This operation drives the moisture from the plaster and leaves a labyrinth of small connected holes in the material at the points previously occupied by the excess water. These holes serve to vent the air inside the mold and the gases introduced by the molten metal as it is poured.

If cores are to be used, they are made in the same way as the mold, baked separately and assembled with cope and drag after the baking period. The mold is then ready to pour.

The plaster of Paris process is usually limited to metals with a melting point not exceeding about 2100 F (except magnesium), but variations of this process are commercially available to cast higher-melting-point metals (up to 3000 F) such as stainless steels. The most popular metals

in decreasing order of their use are yellow brass (Muntz metal or naval brass), aluminum bronze (high iron), manganese bronze, silicon bronze, and occasionally aluminum. Red brass does not have a good surface when cast in plaster molds.

The plaster does not stick to flat surfaces but may adhere to cored or indented sections, and in such cases is usually removed by high-pressure water-stream washing.

Owing to the low thermal conductivity of plaster of Paris in comparison with sand or metal, the molten metal in molds of the former is kept fluid longer. This permits casting sections much thinner than in sand casting or even metal mold casting and there is less danger of internal porosity. However, the structural strength of castings made in plaster of Paris molds is likely to be somewhat lower than that of metal mold or sand castings, especially in those alloys which are given to grain growth, like aluminum.

Typical applications of plaster mold castings are plumbing fixtures; railroad, automotive, and domestic hardware; ball races; gears of all sorts; handles, cams, and levers; covers and boxes; brush holders, terminals, etc. The plaster mold castings are particularly attractive for moderate production parts which would require considerable machining if made in sand, but on account of their limited production would not justify the high tool cost of metal molds. They compete more favorably with brass and bronze metal mold castings than with aluminum.

**12.12. Fusible Material Castings.** The casting of art statuary, dental plates for false teeth, etc., is difficult by regular methods because of the complicated core work. To eliminate the necessity for cores, use is made of a special molding method and of materials which will melt at baking temperatures of normal sand or plaster molds. Such a method was used for making art statuary many centuries ago in China and Japan, and as late as the middle of the sixteenth century in Europe. It is known as the *lost wax* process. Although the commercial application of such a method is limited, it is felt to be of sufficient importance to special problems to warrant consideration here.

The first step is to make a plaster or glue mold of the original model (or pattern) produced by the sculptor. This external mold is then closed and filled with molten wax. After a few seconds the mold is turned over and all the wax not solidified is allowed to run out. The solidified wax forms a thin shell duplicate of the original model, the thickness depending on time of cooling which is chosen in relation to the size of the work.

The hollow wax duplicate of the original model is equipped with

gates and vents in the form of wax rods of appropriate diameters. The mold in which the metal form is to be cast is started by pouring some investment (molding material) around the outside of the wax figure and allowing it to harden. When the outside is completely hard, the same mixture is poured inside, forming the inner mold. It is supported by wires previously inserted from the outer mold. The mold is then baked in the inverted position so the wax may run out, and at the completion of the baking operation, the mold is ready to pour.

At present there are at least two types of industrial applications to which the lost wax method is of importance. One is the preparation of dry sand cores which must contain passages of some curving contour. Such a core might be needed for casting the blades in an integral centrifugal fan. The core is prepared by building up a model of the section to be cast by the core. This model is made from an alloy of low melting point such as Wood's metal or Cerroblose. Sand for the core is tamped in and around the fusible metal structure, and when complete, vented, etc., is baked at a temperature below the melting point of the structure. After the core is dried properly, the temperature is raised, allowing the metal to melt and run out, and leaving a core with which the integral part can be cast.

The second application is to the production of small metal parts of complicated shapes, or of metals which cannot be forged, rolled, or machined by the usual factory methods. For such, it is desirable to be able to economically cast the parts to size, with good surface properties. By proper choice of an investment compound, it is possible to have the investment expand by preheating just as much as the metal will shrink during cooling, and it is thereby possible to control closely the size of the finished casting. The term *precision casting* is sometimes used for this process.

*Electroforming* is another method which makes use of a fusible alloy. As before, a plaster outer mold is made from the model or pattern and a fusible alloy or rubber is melted and poured inside. The fusible alloy or the rubber is solidified and removed from the mold and then its surface is electroplated with copper, iron, or any other metal that can be plated. For plating rubber, it will be necessary to coat the surface by chemically depositing silver, or by rubbing graphite or graphite and silver over the surface, or by some other means so it can carry current. Once the plating is prepared, the fusible metal is melted out, or the rubber is stretched and deformed out. A feature of the plated part is excellent detail and no shrinkage from the original. Depending on the purpose, the electroformed part may be used as the product, or it may be backed with some metal and used as a die for forming operations.

such as embossing, die casting, and engraving. It may also be used for molds for glass, ceramics, rubber, plastics, foodstuffs, soap, candles, hot water bottles, candies, artificial wood, and leather surfaces.

**12.13. Castings in Other Materials.** Both wood and paper have been used for molds of sufficient permanence that they can be used for a small number of duplicate castings provided only low melting point alloys are cast in them. Wood is used for molds of printing designs. The pattern is burned in the end grain of a dried wooden block by shaped steel tools heated to a red heat. The bottom of the impression forms the printing design on the casting. Since the width of the impression is not greater than  $\frac{1}{32}$  in., there is not sufficient metal to give heat enough to damage the impression. As many as 50 to 100 castings can be produced. Paper molds are made from several layers of tissue paper pasted together and backed by damp unsized paper. They can be used as molds for full pages of type, including illustrations. When dry, the mold thus formed is mounted on an iron support to receive the molten metal.

#### METAL MOLD CASTING

By D. BASCH and J. F. YOUNG

**12.14. Metal Mold Processes.** Both sand and plaster of Paris molds are single purpose molds; that is, they are completely destroyed when the casting is removed. Thus a new mold must be prepared for each casting to be made. For that reason, considerable savings in labor and material are realized if a "permanent" mold is made which lasts for the required number of castings. Such permanent molds are made from metal. They are not recommended when only a few castings are to be made because the cost of the metal dies would greatly exceed the cost of the individual sand or plaster molds. In addition, the absence of metals which will withstand very high temperatures and the difficulty of making large metal molds makes them unsuitable for large castings or for alloys of high melting temperature. The metal mold processes are more favorably used for small and medium size castings made in large quantities.

The methods of casting which utilize metal molds are classified as follows:

1. Permanent mold casting.
2. Semi-permanent mold casting.
3. External pressure casting:
  - a. Die casting.
  - b. Cold-chamber pressure casting.
4. Centrifugal casting.

The favorableness of each of these methods depends on the design of the part, the metal used, the quantity of castings to be made, and the effect of the quality of the casting on subsequent manufacturing costs. To better evaluate these points, each method will be considered separately.

**12.15. Permanent Mold Castings.** In this casting method, fluid metal is poured by hand into metal molds and around metal cores. The only pressure applied is that of 2 or 3 lb per sq in. exerted by the head of metal in the pouring gate. The molds are usually held together by C-clamps, although in some cases they are closed and opened by a screw or a toggle mechanism.

Both ferrous and nonferrous metals may be cast. Dies for the alloys of very low melting point are made from bronze; iron and steel molds are used for the nonferrous castings; and for permanent mold iron castings, steel molds are coated with refractory material. The latter molds are usually cast with allowance for machining and refractory material if it is to be used during casting. Such a refractory helps reduce erosion and checking, but it must usually be renewed every day and the casting is never as smooth nor as accurate in dimension as castings which contact the polished metal die surfaces. In this respect, they are superior to sand castings, however. They also have better structure than sand castings and greater freedom from steam and gas holes. Metal cores may be made from other castings or from wrought materials.

For making iron castings of this type, turntables on which a number of metal mold units are mounted are frequently employed; and the individual operations — such as coating the mold, placing the cores, closing the mold, pouring, opening the mold, and ejection of the casting — are performed as each mold passes certain stations. The castings are usually annealed to avoid white iron in any corners which may not have been properly heated (preheating), coated with refractory, or smoked with carbon. The anneal also relieves any strain that may be set up.

Of the many metals suitable for this type of casting, aluminum and its alloys are used the most, magnesium next, and the copper-base alloys other than the brasses are third. Aluminum-base metals are molded this way, even though the lack of pressure reduces tensile strength somewhat, because there is less porosity in the casting than when made by other methods. In addition, heat treatment offers less difficulty than with die castings which are subject to porosity and blistering. Therefore some heat treatable alloys are cast, giving higher strength through heat treatment.

Copper-base materials include the bronzes, particularly the high-iron aluminum bronzes which are gaining in importance for gears, bushings, etc. Iron is perhaps fourth in importance. Lead is used for making battery grids and connectors, but the alloys of zinc and lead are used chiefly for permanent mold slush castings.

In the slush casting process, the metal is held just long enough in the metal mold to permit the outer "skin" to harden, then the mold is upended and the liquid core of the casting is allowed to run out, thus leaving a hollow, thin-walled shell; the thickness of the wall can be controlled by the pouring temperature, the time interval between pouring in and out, etc. The inside wall contour and therefore the wall thick-



FIG. 12.13. Zinc slush casting. Note irregular wall thickness.

ness is always irregular. This is illustrated by the slush casting shown in Fig. 12.13. Typical products made by the slush process are toys, handles, teapot spouts, fancy borders and trimmings, novelty clocks, candlesticks, lamp stands, electric light fixtures, and ornamental objects that may be finished in silver, gold, or bronze.

Summarizing, the permanent mold method provides castings having these advantages: (1) Dense fine-grained structure, free from shrink holes or blow holes; (2) relatively low tool charges; (3) lower mold cost than for other metal mold methods to be discussed; (4) better surface and closer tolerances than provided by the sand cast method.

On the other hand, the method has these limitations: (1) Inability to maintain as close tolerances and as thin sections as will the external pressure or plaster of Paris casting methods; (2) yellow brasses, which are high in zinc, are difficult to utilize because of zinc oxide fouling the mold or dies; (3) the production rate is slower than for the same parts made by other metal mold methods.

**12.16. Semi-Permanent Mold Castings.** This method is the same as that for permanent mold castings except that sand cores are used at

some points instead of metal cores. The use of sand cores results in lower tool cost and also allows cored openings of irregular shape, or undercuts such that metal cores would be too costly or too difficult to handle (large or deep, etc.) on a production basis. Most applications make use of this latter possibility. Fig. 12.14 is an example of a semi-permanent mold aluminum casting.

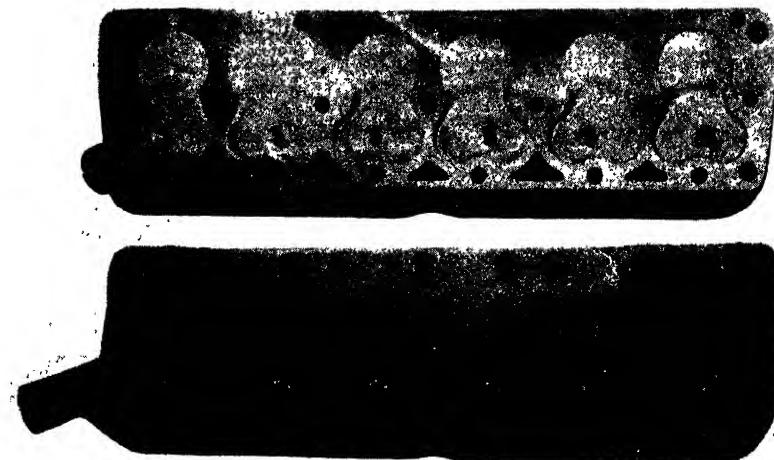


FIG. 12.14. Semi-permanent mold aluminum cylinder head typical of those produced in vast quantities for many internal combustion engines. (*Courtesy Aluminum Company of America.*)

The metals suitable for casting by this method are the same as for the permanent mold method, but the speed of production is somewhat reduced.

Another disadvantage of the method is that the structure of the metal around the sand cores and the dimensional inaccuracies, core shift, etc., are the same as for sand casting. The advantages of casting tolerances, density, appearance, etc., as for permanent molds, exist only in the section cast against the metal mold. Several castings made by permanent and semi-permanent metal molds are illustrated for comparison in Fig. 12.15.

**12.17. External Pressure Castings.** In this process, highly fluid metal is forced under considerable external pressure into metal molds, the pressure being maintained until solidification is complete.

The metal molds or dies comprise at least two blocks of alloy steel,

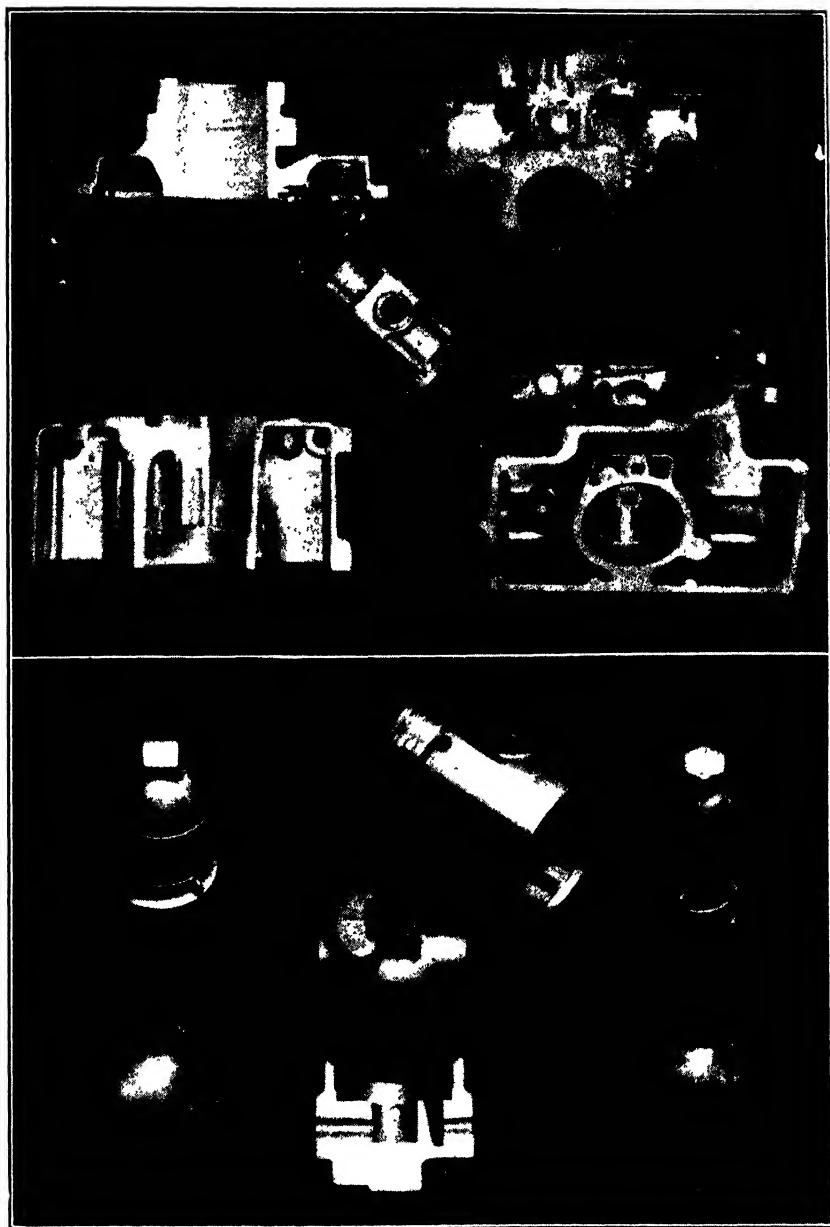


FIG. 12.15. Examples of semi-permanent and permanent mold castings. Note cut parts showing the contour of the cross-section. (*Courtesy The Permold Company.*)

each containing a part of the cavity, which are locked together while the casting is being made, and drawn apart when it is ready for ejection. One half of the die (next to the injector nozzle) is stationary, and the other half moves on a carriage. Both halves are sometimes artificially cooled to hasten the solidification and the removal of the casting from the die.

As the die opens, the casting remains in the movable half of the die. This half often contains core pins or other male portions upon which the casting shrinks in cooling. Mechanically operated ejector pins push the casting off these pins and projections and free of the die.

Aside from changes in dimensions of the die block resulting from heat expansion and contraction and from minor wear on die surfaces, the dimensions of the cavity remain substantially fixed, thus facilitating repetitive production of castings having small dimensional tolerances.

The many different machines used commercially to open and close the dies, introduce the molten metal, eject the casting, etc., may be divided into two classes: (a) those in which the casting mechanism is constantly immersed in hot molten metal, and (b) those in which the mechanism is immersed only for short intermittent periods.

Castings made by machines of the first class are called *die castings* and those of the second, *cold-chamber pressure castings*. Both classes are called *squirt castings* (spritzguss) in Germany, and *pressure castings* in England where the term "die casting" is applied generally to a casting made in a metal mold by any of the methods. The terminology used in the United States has been established too firmly, however, to consider changing to the more distinguishing terms.

**12.18. Die Castings.** Die castings are produced in machines which consist basically of a basin holding a considerable quantity of molten metal (enough for several hours' production and continually replenished), a metallic mold or die, and a metal-transferring device which automatically withdraws a certain amount of molten metal from the basin and forces it under external pressure into the die.

The oldest form of die casting machine is the so-called piston machine shown schematically in Fig. 12.16. Lead, tin, and zinc alloys containing aluminum (Zamak alloys) are handled in this machine at pressures ranging from a few hundred to 5000 lb per sq in. The best practice for zinc-aluminum alloys is to use a minimum of about 1000 lb per sq in.

Aluminum alloys, pure zinc, or zinc alloys free from aluminum require a different type of casting machine since these materials rapidly attack the iron in the piston and cylinder and destroy the required close fits. The gooseneck machine shown schematically in Fig. 12.17 was developed to eliminate this difficulty. In this machine, the gooseneck serves as

the device for transferring the molten metal from the metal container to the die opening, and air pressure applied externally forces the metal into the dies. The air pressure that may be applied is limited to a maximum of 700 lb per sq in. (350 to 550 lb per sq in. on the average).

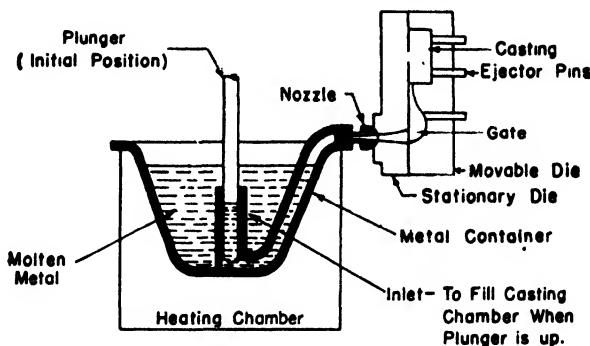


FIG. 12.16. Typical piston type die casting machine. The plunger, heating chamber, metal chamber, and die carriage are parts of the same machine.

With Zamak alloys, this results in a structure somewhat less dense than that from the piston machine.

At its melting temperature, aluminum strongly attacks the iron in the gooseneck and the metal container, especially when in continued

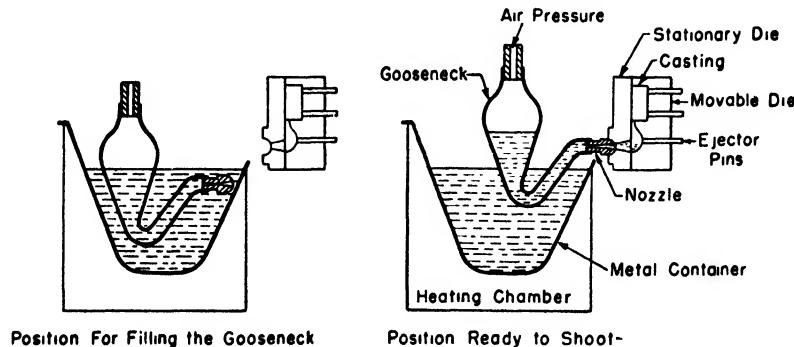


FIG. 12.17. Typical gooseneck type die casting machine. The gooseneck, metal container, heating chamber, and die carriage are parts of the same machine.

contact, with the result that the metal used for aluminum castings to be made with the gooseneck machine will practically always show an increase in iron content. This is a disadvantage because iron in aluminum adversely affects the ductility, castability, machinability, shock resistance, etc. When the aluminum castings must contain less than

2 per cent of iron, they are frequently cast by the cold-chamber or the permanent mold process to avoid this difficulty.

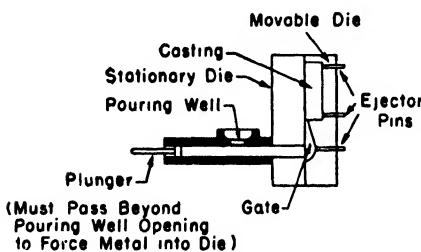
Both the piston machine and the gooseneck machine are limited to casting metals which have a melting point not exceeding 700 C. The strength of the machine parts operating in constant contact with the molten metal and at its temperature impose this limit. Even so, the pistons require repair on the average of once a production month, and the nozzles require replacement much more frequently.

**12.19. Cold-Chamber Pressure Castings.** Cold-chamber pressure castings are produced in machines which are fundamentally different from the die casting machines shown in Fig. 12.16 and 12.17 in that the molten-metal reservoir is separated from the casting machine, and just enough metal for one shot is ladled into a small chamber, or pouring well, from which it is forced into the die under high pressure. (See Fig. 12.18.) There is no limitation to the pressures back of the metal, pressures as high as 16,000 or even 20,000 lb per sq in. being employed in some cases. Usually, however, lower pressures of the order of 3000 to 10,000 lb per sq in. are used to facilitate the mechanical problem of making the machine heavy enough to provide the locking and holding powers to keep the two die halves together without opening up under the tremendous impact of the injected metal.

FIG. 12.18. Sketch of cold-chamber pressure machine. The plunger, cylinder, and die carriage are parts of the same machine. The melting pot and metal container are separate.

The relatively short exposure of the pouring well, cylinder, and piston to the molten metal permits casting of alloys of high melting point such as brass and bronze. It also minimizes the absorption of iron from these parts and thereby enables production of low-iron aluminum castings.

The added pressure is also important to the type and quality of castings that can be made. The greater the pressure back of the metal, the greater the compressive force on the metal as it passes through the pasty stage, and the greater the force to compact the structure and to press the hot metal through narrow channels, into sharp corners, crevices, etc. Thus cold-chamber pressure castings give greater promise of close grain, nonporous structure, sharp outline, and extremely thin section than die castings. These results cannot be obtained, however, unless expert metallurgical and production control are exercised, and dies are



most carefully gated and vented (vents allow the air ahead of the incoming metal to be driven out of the die rather than to mix with the molten metal).

Besides castings of copper and aluminum alloys, the process is applicable to magnesium alloys and zinc alloys. Although the production speed of the cold-chamber process is less than that of the piston process (because of the ladling operation), the over-all speed is about the same because of the "down" time for maintenance in the die casting process.

**12.20. General Characteristics of External Pressure Castings.** In the two previous sections, a number of the fundamental differences between metal mold external pressure castings were mentioned. Aside from such differences, all these castings share certain properties, although to a varying degree. They all have close tolerances, sharp outlines and contours, a fine smooth surface, and high speed of production with low labor cost. They all have a hard "skin" with a softer core, owing to rapid chilling of the surface of the casting in contact with the artificially cooled metal mold. Consequently, machining the surface will disproportionately reduce the strength of the section and will cause warping on account of the release of internal stresses held in check by the skin as long as it is unbroken.

If the molten metal is introduced into the mold at high velocity, there is a tendency for the molten metal to trap air and oil vapor in the die and occluded gases in the metal, as illustrated in Fig. 12.19. There is also some spraying action which makes possible oxidation of small metal globules. Both these actions promote a porous nonintegral core structure. Machining such castings will reduce the leakage resistance to internal pressure, so, in general, it is inadvisable to machine deeper than 0.010 in. maximum. Exposure of these castings to high temperature may produce blistering of the surface because of the expansion of gases trapped inside the casting by the rapidly hardening skin.

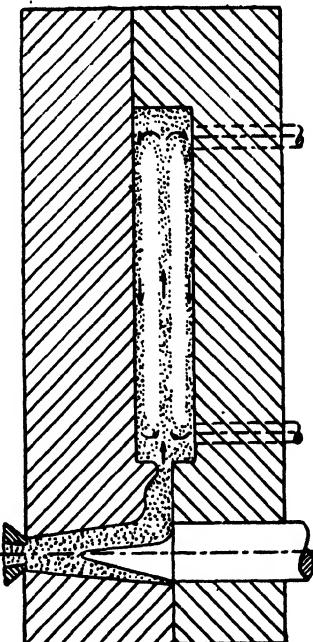


FIG. 12.19. Sketch showing how air and vapor are trapped in a casting when the molten metal is squirted into the die.

This tendency limits use of these castings for cooking utensils or heating apparatus, and prevents use of metals which could be hardened by heat treatment.

In a recent development, molds for castings of certain design have been filled in such a way that gas holes and globule oxidation are eliminated. Details of this method are not yet available, but it has the advantage that the nonporous castings are stronger and are not subject to blistering at elevated temperatures. This characteristic suggests that the method may have many applications for castings that must be heat-treatable or used in relatively high temperature applications.

Internal shrink holes are more apt to occur with die casting than with cold-chamber casting. They may be caused by:

(1) *Uneven Chilling.* The heavy sections shrink last, and if the metal between the heavy sections and the pressure at the sprue becomes frozen first, a hole (or a depression of the outside if the wall is weak) will result at the heavy section. Design can correct this.

(2) *Drossy and Sluggish Metal.* When a metal is contaminated with too much iron and other impurities, its flow becomes sluggish and it chills before its shrinkage is fully satisfied. Die casting metal might contain impurities because of continued contact with the metal container.

At the present time, cold-chamber pressure-cast brasses and bronzes have not yet found the same wide popularity as zinc and aluminum die castings or cold-chamber pressure castings, although excellent products have been turned out. The main difficulty lies in the high cost of the dies, since the tool-steel industry has not yet been able to produce a steel for the dies which will last as long at the high temperature at which the cuprous alloys are cast as die steels for aluminum or zinc. Further, dies for zinc sometimes do not need heat treatment. Plaster of Paris and permanent mold castings are still competing favorably with cold-chamber pressure-cast brass or bronze, except where production is so large and savings in machining due to the closer tolerances so considerable that the high cost of molds for the cold-chamber pressure castings can be absorbed. Competition between permanent mold and die castings is mainly between alloys of the same metal rather than different metals.

**12.21. Centrifugal Castings.** The centrifugal casting process consists in pouring molten metal into a sand-lined mold, or a permanent metal mold, which is revolving at a speed ranging from 600 to 3000 rpm. depending upon the diameter of the casting and the alloy to be used. The centrifugal action forces the molten metal tightly against the mold,

and the metal solidifies with its outer surface conforming to the mold shape.

The basic shape produced by this process is a thin or thick walled hollow cylinder with a straight bore concentric with the outside — the wall thickness depending on the amount of metal poured.

Although the free internal surface will always be a surface of revolution, the outer surface may be hexagonal, square, octagonal, or round, etc., with or without flanges or grooves. Occasional bosses or protuberances breaking the symmetry of the perimeter may also be cast provided they are not too high or too thin. Flanges, bosses, etc., should not be much thicker than the wall of the cylinder so that internal stress resulting from unequal cooling will not be excessive. It is not good practice to attempt to cast centrifugally two flanges on opposite ends of a long tube because during cooling both would act as an anchor and prevent normal shrinkage of the casting.

Refractory cores are used in this process for the purpose of producing irregularly shaped inside walls. In the majority of instances, however, the inside of the casting is machined to remove the impurities which gather there. These impurities include slag, oxides, pieces of refractory, etc., which are lighter than the metal, and are squeezed out of the rotating mass to the inside under the influence of the greater centrifugal force on the heavier metal.

The elimination of drossy metal from the body of the casting is only one of the metallurgical benefits of the process. Others are finer grain size, slightly increased density, uniform distribution of alloying elements, and elimination of the internal centerline weakness caused at the boundary of two separate columnar growths which occur when a casting is cooled simultaneously from two sides. These factors account for as much as 20 per cent increase in the strength of centrifugally cast parts compared with still castings. Elongation and hardness will also show an increase.

Other advantages of the process are the low cost of molds, the applicability to large and long, hollow shapes, and the casting of any metals, especially those difficult to work by forging.

The inner bore of the centrifugal casting will be a straight cylinder when the axis of rotation is horizontal. When the mold is rotated about a vertical axis, however, theoretically a paraboloid will result because of the effect of the gravitational force. Slightly concave or convex sections can therefore be obtained by proper control of speeds, but at the higher speeds this effect becomes increasingly smaller and the bore will be essentially straight.

Recently some experimental work has been done on obtaining special inside shapes by inclining the axis of rotation and by rotating the mold about two axes simultaneously. This phase of centrifugal casting may have potential commercial application in the future.

The limitations of the centrifugal casting process are:

(1) Castings located concentric to the axis of rotation must have a through hole, and extra metal must be provided for machining on the inside of this hole when impurities are present in the metal.

(2) Because of the comparatively high speeds of rotation and the large masses ordinarily cast, the parts should be dynamically balanced. Although small amounts of unbalance are sometimes tolerable such as, for example, small ports in cylinder liners, any considerable unbalance will overload the bearings and structural members of the casting machinery excessively. Hence, when fairly large holes are required in the casting in such a location that they would contribute to the dynamic unbalance of the part, they are machined afterward, the part being cast solid.

(3) Close tolerances and sharp outlines are obtainable only at the periphery. In castings located eccentric to the axis of rotation of the mold, the outlines near the center of rotation will not be as sharp as those at the outer circle.

Typical applications include gun shells, gear blanks (grain especially good), long steel cylinders, pipes, pressure vessels, piston rings of small eccentricity, bushings, Babbitt liners, squirrel cage rotors of small induction motors, and other similar articles in most any castable metal.

**12.22. Design of Metal Mold Castings.** Metal mold casting involves the pouring and solidification of molten metal, as in sand casting, and the use of metal dies, as in plastic molding. As a result, the design of metal mold castings gives rise to a combination of the problems encountered in designing sand castings and plastic parts, and makes use of many of the techniques already discussed for designing these parts. Of the many techniques mentioned, the following should be incorporated in the design of metal mold castings, particularly external pressure castings, whenever possible.

(1) For low die cost, parting lines should be in one plane, preferably at right angles to the tie bars which guide the movable half of the die.

(2) Both internal and external undercuts should be avoided when possible. Undercuts on the outer surface necessitate a separate slide, and cores or male die parts cannot have undercuts without introducing other complexities in die construction; thus undercuts increase die and production costs.

(3) Sections should be uniform, and any changes in section thickness

should be made as gradual as possible. Fig. 12.20 illustrates two examples of designs modified to obtain more uniform sections.

(4) Section junctions should be joined by fillets, especially where these junctions are subjected to service stresses, because the fillets reduce stress concentration and give a crystalline structure which results in stronger castings. Sharp corners in molds may also retard metal flow or cause eddies and trap air, thus proving disadvantageous from the casting standpoint.

(5) Ribbing is desirable on thin sections of considerable area, especially when flat, not only to give stiffness and to minimize warpage,

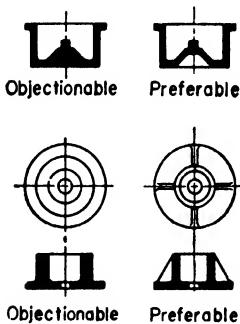


FIG. 12.20. Examples of design changes resulting in uniform sections.

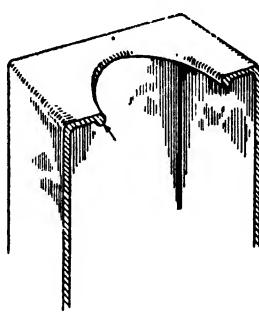
FIG. 12.21. Box showing use of a bead.

but also to provide feeder channels of larger cross-sectional area. Without such channels, a large flat surface may not fill out, particularly when the die is cold.

(6) Ribs or beads may also be used to strengthen thin sections (Fig. 12.21) where trimming of flash is required. Such beads improve appearance, diminish chances of warping, and reduce trimming costs.

(7) Bosses and other heavy sections, when used, must be so designed that they can be fed with molten metal from the gate. Bosses isolated from the gate by a thin section will contain a shrinkage cavity since their contraction cannot be made up with molten metal. Liberal fillets should be allowed where the boss joins the supporting sections. Bosses are often used around inserts to stiffen the casting where the insert projects. Heavy bosses should be used around holes in which taper threads are tapped to avoid the likelihood of the casting being split or cracked when a plug or connection is screwed in.

(8) Letters, numbers, trademarks, stippling, or knurling should, for low die cost, be raised on the die casting, and sunken on the die as for plastic parts. Undercuts should be avoided by putting engraved or



lettered surfaces parallel, or nearly parallel, to the parting line, otherwise an extra slide or movement is required in the die. If it is undesirable for the lettering to be raised from the surface of the part, the whole lettered section can be sunk into the casting to the depth of the letters.

(9) The slenderness of core pins for bottomed and through holes must be limited as in plastic molding to prevent the pins from breaking or bending excessively under the action of the metal entering the die at high velocity and under high pressure. Although intersecting cores are often used successfully, their use is best avoided, if possible, because bending and wear may cause them to become misaligned.

Some other points which should be considered when designing metal mold castings are discussed in the following paragraphs.

*Cores.* Aside from the slight difference involved in the cost of machining the cores, a cored hole may be made square, hexagonal, splined, or of odd shape as cheaply as of truly circular section. In this respect a die cast piece with an odd-shaped hole is usually much less costly in quantity production than one made by other means than casting. A bushing with a splined external diameter is sometimes die cast and forced onto a shaft so that the expense of splining the shaft can be avoided.

When convenient, the core should have its axis at right angles to the parting face, that is, parallel to the direction of motion of the die blocks, as it is then most easily removed or the piece stripped from it. Cores can be pulled at any angle, however; and many types of mechanism, either manual or machine-operated, are adapted for this purpose. Some machines have more or less "standard" core-pulling mechanisms. Others require special rigging, special slides or other special operating means, which may be a part of the die or of the machine itself.

*Special Cores.* Where undercuts are required, use may be made of collapsible cores which are in several sections so designed and assembled that a key section can be withdrawn easily, leaving the others then free to be removed. An example is the collapsible core arrangement used for making a vacuum cleaner housing (Fig. 12.22). Sometimes crooked cores are made up from loose pieces or knockouts designed to clear the part when removed separately, but not as an assembly. The kettle spouts illustrated in Fig. 12.23 are good examples. For other undercuts, straight cores may be combined with one or more loose pieces which are knocked out when the main core has been withdrawn. This type of core is illustrated in an elbow with an inside fillet (Fig. 12.24). The loose piece may be avoided by using a square inside corner or by employing a core which may be rocked into place as illustrated in that figure.

Crooked channels from which cores could not be withdrawn are made by using a drawn tube, bent to the desired shape, as an insert and casting it in place. This is sometimes done to provide an oil channel from one point to another in the body of a casting, thus making it possible, for

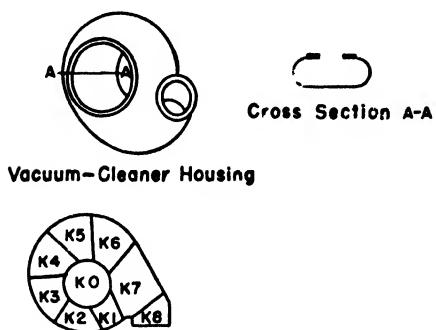


FIG. 12.22. Collapsible core used for casting a vacuum cleaner housing.

To be Withdrawn First

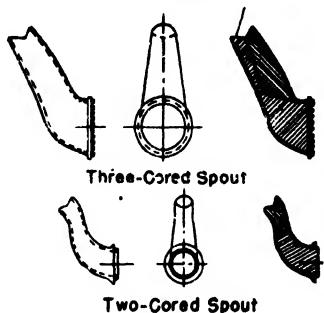


FIG. 12.23. Coring for die cast kettle spouts.

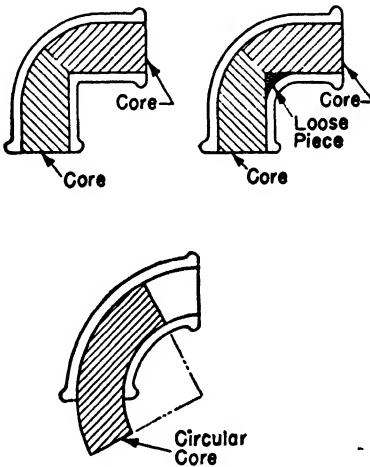


FIG. 12.24. Cored elbows illustrating two methods of avoiding use of a loose piece.

example, to feed two bearings from a single oil supply without external piping.

Although undercuts can be cast by these and similar techniques, they involve complications and often slow the casting operation. Sometimes the end justifies the means, but frequently the design can be changed

to avoid the necessity for undercuts, as in Fig. 12.25, or the undercut may be machined rather than cast. An annular groove inside a hole is easily machined but difficult or impossible to core.

*Threads.* Internal threads are made by a stud core which must be unscrewed from the piece. This tends to slow production, unless some special provision is made on the machine or die to perform this automatically; so it is usually cheaper to tap all holes which are to be threaded. When the holes are not too large, they may be cored to the root diameter (minus draft or taper) and then require no drilling before tapping. Sometimes it pays to punch or drill holes for tapped threads rather than to core them. This is especially true for small holes which would leave a thin flash or fin that would have to be cleaned out anyhow. A conical spot core which spots the drill will speed up the drilling operation.

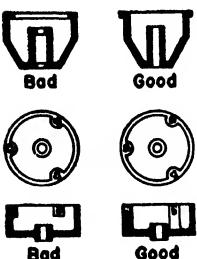


FIG. 12.25. Design changes to avoid undercuts. Aluminum or brass alloy internal threads are seldom cast because the large shrinkage of these metals may result in galling as the stud core is removed.

External threads may be made by a threaded collar which must be unscrewed, but more frequently, because of the faster production, they are made by a split section die. A small fin is left where the split or parting is made, so the thread must be die chased if a close fit with a mating part is required.

The Whitworth form of thread which has a rounded root and crest is the easiest to die cast and is often used with another die cast Whitworth thread. But where the die cast thread must mate with a machined thread, the U. S. standard form is used because the machining is much enhanced. Square threads may be die cast, but require complicated coring because of the undercutting. Tapered pipe threads are readily die cast, although for a tight accurate joint, they are usually chased with a cutting die. Many die cast threads are used as cast, except for fin removal, where exceptional accuracy is not required. Shrinkage of the piece causes an error in pitch but this is not of significance unless the thread is unusually long.

*Inserts.* Die castings and also cold-chamber pressure castings sometimes employ cast-in inserts of dissimilar metals, or nonmetallic elements, to impart locally to the casting certain properties which the cast alloy itself does not possess. These properties may include higher strength, greater hardness and wear resistance, special electric or magnetic paths, or superior bearing qualities. The inserts are placed in the die before the casting is made and must be securely positioned. Since

they are usually placed in the hot die by hand, their use lengthens the cycle and reduces the production rate; so they can be used only when the increased cost is justified by the benefit obtained. The most common insert is a screw-machine product of steel or brass, but stampings, forgings, and even sand cast or die cast inserts have been used to advantage. When using inserts of metal other than that of the casting itself, the possibility of electrogalvanic corrosion should be considered.

Inserts are usually knurled on the surface, or undercut, or provided with projections or holes which anchor them securely when metal is cast around them and prevent them from turning or pulling out of the casting. When plated inserts are to be used in zinc castings, they should never be tin- or cadmium plated, as such plates would seriously affect the chemical stability of the casting.

Bearing inserts may be of almost any metal, such as graphited bronze, porous bronze (porous-bronze inserts should not be oil-filled until after the casting has been made), hardened steel, or even wood or a molded phenolic when used with zinc alloy. The molten zinc entering the mold solidifies quickly and barely discolors the surface of the wood. Hardened steel inserts may be cast-in without losing their tempered hardness. Bearings and bushings, if accurately machined before insertion, require little or no machining after casting in place, as they can be positioned quite accurately on cores or fixed pins. At most, only a little reaming of the bore should be required after casting. Some die casting alloys and cold-chamber pressure alloys, especially zinc base, have good bearing qualities, so they do not always require a bushing insert for a bearing.

*Gears.* Any type of gear with a tooth form which will clear a die can be die cast or cold-chamber pressure cast. Although the majority of gears cast by these processes are for light mechanisms, some for quite heavy service have been made. For light lathe applications, with gears running dry, greater wear resistance has been attained with die cast zinc-alloy spur gears than with gray cast iron machined gears.

Die cast and cold-chamber pressure cast spur and internal gear teeth, in general, have to be given a slight draft, at least if the face width is considerable; hence the tooth elements are not exactly parallel unless a shaving or equivalent machining operation is performed. Some other forms of teeth, such as those for bevel gears, are die cast or cold-chamber pressure cast with substantially perfect tooth form without machining. Internal gears are as easily die cast or cold-chamber pressure cast as those of the external or spur type and both may have teeth shrouded on one side with resultant strengthening, whereas cut gears of this type are difficult and expensive to machine. (See Fig. 12.26.) It is also an easy matter to die cast or cold-chamber pressure cast a square or splined

TABLE 12.1. TOLERANCES FOR METAL-MOLD CASTINGS

[These data should be used for general guidance only. Actual design conditions will affect possible minima or maxima.]

Manufacturing Method	Metal	Tolerances Within Solid Die in Inch per Inch	Minimum Wall Thickness in Inches <sup>1</sup>	Minimum Hole — Dimensions		Minimum Draft per Side per Inch of Depth of Side Wall or Holes Inch per Inch <sup>1</sup>	Remarks:
				Maximum Diameter in Inches	Maximum Depth by Diameters		
Die and Cold-Chamber Casting	Magnesium Alloys	$\pm 0.0015$ , but at least $\pm 0.003$	0.050 for small sections. More for larger sections.	Smaller than $\frac{3}{32}$	Not cored 3 times 3 to 5 times	$0.010$	
	Aluminum Alloys	$\pm 0.0015$ , but at least $\pm 0.003$	0.035 for small sections. More for larger sections.	Smaller than $\frac{3}{32}$	Not cored 3 times 3 to 6 times	$0.010$	

Die and Cold- Chamber Casting	Zinc Alloys	$\pm 0.001$ , but at least $\pm 0.0025$	0.020 for small sec- tions. More for larger sections. $\frac{3}{16}$ to $\frac{1}{4}$ $\frac{1}{4}$ to 1	Smaller than $\frac{3}{16}$ Generally not cored.	0.005
	Brass and Bronze	$\pm 0.003$ , but at least $\pm 0.005$	0.050 for small sec- tions. More for larger sections. $\frac{3}{16}$ to $\frac{1}{4}$ $\frac{1}{4}$ to 1	Not cored 2 times 2 to 4 times	0.015
Magnesium Alloys	$\pm 0.0015$ , but at least $\pm 0.010$	0.1875 (regardless of whether sur- face is rough or smooth).	Smaller than $\frac{1}{4}$ $\frac{1}{4}$ to $\frac{1}{2}$ $\frac{1}{2}$ to 1	Generally not cored 3 times 3 to 6 times	0.015
	Aluminum Alloys	$\pm 0.0015$ , but at least $\pm 0.010$	0.125 (0.090 where at least one side can be reason- ably rough).	Smaller than $\frac{1}{4}$ $\frac{1}{4}$ to 1	Generally not cored. 3 times 3 to 6 times
Perma- nent- Mold Casting	Bronze	$\pm 0.005$ , but at least $\pm 0.010$	0.075 for small sec- tions. More for larger castings. $\frac{1}{4}$ to $\frac{1}{2}$ $\frac{1}{2}$ to 1	Smaller than $\frac{1}{4}$ $\frac{1}{4}$ to $\frac{1}{2}$ $\frac{1}{2}$ to 1	Generally not cored. 2 times 2 to 4 times
	Brass and Bronze	$\pm 0.003$ , but at least $\pm 0.005$	0.032 for small sec- tions. More for larger areas. $\frac{1}{8}$ to $\frac{1}{2}$ $\frac{1}{2}$ to 1	Smaller than $\frac{1}{8}$ $\frac{1}{8}$ to $\frac{1}{2}$ $\frac{1}{2}$ to 1	Generally not cored. 3 times 3 to 6 times
Plaster of Paris Casting					0.020 -
					0.010

The minimum wall section that can be cast with different alloys and by different processes is not absolutely fixed. It depends on the size and design of the casting, on the location of the section with reference to heavier adjacent sections, on the die, the alloy, type of machine, and the pressure applied. In general, the lower the melting point and the more fluid the metal, and the shorter the distance between the chipping walls of the die or mold, or the faster it traverses the distance, the thinner the wall may be. There is practically no limitation on casting heavy wall thicknesses, as may be encountered in commercial applications. Sections somewhat heavier than minimum castable are recommended (especially for die and pressure castings) when castings are to be plated, as they hold greater promise for smooth surface.

Fins: Metal-mold castings can be finished with three different finishes, as follows, and should be marked on drawings to designate type of finish desired.

No marking — Commercial: Standard finish produced by commercial, but carefully controlled, routine

Decorative: (Required for plating.) Free from flow marks and from swirls and other surface imperfections.

Poorer than commercial: suitable for unexposed or painted surfaces.

hole in the hub or to split the hub for clamping to a shaft, whereas it would cost much more to obtain similar results by any other process.

Worms and worm wheels are readily cast by either the die or cold-chamber pressure methods, although for precision gears of this type, on which very smooth tooth surfaces are required, some machine work is necessary, and allowance for this must be made in the casting.

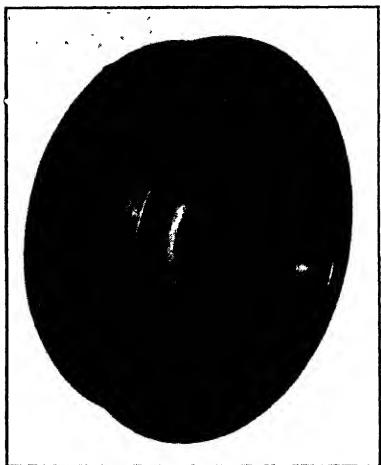


FIG. 12.26. External pressure casting with internal gear teeth and shrouded, toothed hub.

to cast to even closer tolerances or smaller size, but the die caster should be consulted on such designs before they are settled. Fig. 12.27 is an example of a die casting made with a relatively thin section.

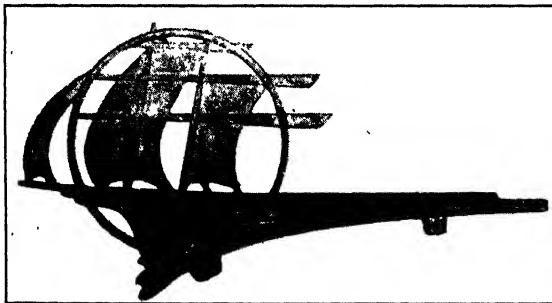


FIG. 12.27. Thin die cast radiator ornament.

**Finished Surfaces.** Parts can be plated most inexpensively and for best appearance and protection if the following conditions can be observed in the design.

- (1) Avoid deep, narrow, closely spaced ribs. They entrap buffing

compound, are difficult to clean properly, and are hard to plate since the front faces absorb most of the plating current.

(2) Recesses in which gas can be entrapped should also be eliminated. These areas will not be plated and the flow of excess gas over the surrounding surfaces may cause peeling and poor appearance.

(3) Generous radii in re-entrant angles avoid the necessity for applying excessive thickness of plate to assure meeting minimum coating requirements in these areas.

(4) Sharp outside corners and points should not be included in the design because deposits on such areas tend to be rough and brittle.

(5) Large concave areas are difficult to plate because of low current density at the center. Convex shapes are easier to plate than flat shapes.

(6) Since a plated part must be buffed, a brilliant luster cannot be obtained in those areas which the buffing wheel cannot reach.

Unless otherwise specified, die and cold-chamber pressure castings are supplied with a commercial surface finish, that is, the best obtainable in regular routine with modern machinery and with up-to-date and carefully controlled metallurgical and casting practices. Such a finish is reasonably free from surface imperfections, such as pits, draws, run marks, and scabs.

Where a better finish is required, it must be requested of the die caster. Such a finish naturally costs more than the commercial finish. When castings are used in locations where the surface appearance is of no importance, even the commercial finish would not be needed and a subcommercial finish would save some cost.

Large flat surfaces are difficult to make exactly flat, and when polished the irregularities will be shown up by reflected light. For that reason large surfaces are frequently given a slight curvature, or are finished with beads, trimming, etc., to break up the large flat area. When heavy ribs are used under a surface, the beading should be opposite the ribbing to eliminate the possibility of shadow marks occurring because of slight indentation of the metal when the rib cools. Fig. 12.28 shows a bead used to avoid a shadow mark.

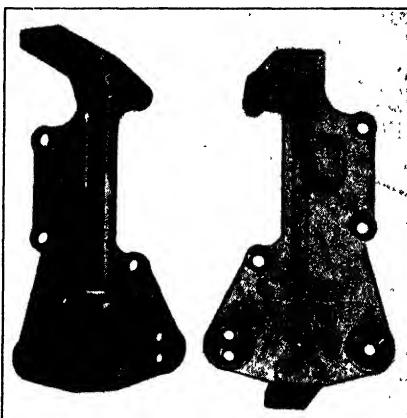


FIG. 12.28. Two views of a casting showing rib and shadow bead.

The scope of metal mold castings, particularly of die, cold-chamber pressure, and permanent mold castings, can be enlarged materially through combination with other manufacturing processes, such as cold forming and punching. Fig. 12.29 shows a die cast pull knob for a refrigerator vegetable drawer, cast with a straight skirt which is afterwards cold formed into spherical shape. Hollow box sections are frequently cast as an open U and afterwards transformed into a closed box by bending part of the U over at right angles. When other separate



FIG. 12.29. Door knob made by die casting and subsequent cold forming of the skirt.

parts are to be riveted to die castings, pins are sometimes cast integrally with the die casting proper, and riveted over after assembly. Such cold-forming operations are usually performed on zinc die castings, although new aluminum alloys are now available which lend themselves to the same process.

**12.23. Choice of Metal Mold Casting Process.** The final selection of the metal mold casting process, in competition with sand casting or any other method of manufacture, will depend on the best balanced combination of (a) suitability of the material under consideration and physical characteristics imparted to it by the process; (b) competitive and advertising advantages through the use of the process; (c) cost of tools and of each piece in a finished state, inclusive of all machining; (d) total saving in cost of all finished pieces during the period allowed for the liquidation of tools.

The physical properties imparted by the various casting processes have been summarized in Table 12.2. This table should be of value to the engineer in estimating suitability of both material and process.

TABLE 12.2. RELATIVE CHARACTERISTICS OF DIFFERENT CASTING METHODS  
(Numbered in order of preference)

Casting process	Sand	Plaster of Paris	Permanent mold	External pressure		Centrifugal (in metal molds)
				Die	Cold chamber	
Materials suitable for process	All casting metals	Yellow brass bronzes Zn, Pb, Sn	Al alloys bronzes iron Zn + Pb	Zn alloys (containing Al) Al alloys Pb + Sn	Al alloys brass bronze Mg alloys Zn alloys (no Al)	Al alloys brass, bronze, Monel, iron, and steel
Porosity	6	2	13	5	4	21
Surface smoothness	6	1	14	2	3	15
Sharpness of casting outline; dimensional tolerances	6	1	14	3	2	15
Strength (solid metal)	5	6	3	2	1	24
Thickness of section	5	1	4	3	2	6 (as cast)
Tool cost (pattern and molds) <sup>3</sup>	1	3	4	5	6	2
Speed of production and labor cost per casting <sup>3</sup>	On basis of most economical tool setup (as to number of impressions on one pattern plate or in one die) for comparative production quantities.					
	For small and moderate production inclusive of setting up of die:					
	1	2	4	5	6	3
For large production						
Possible savings for machining	6	5	3	1	2	4
	5	1	4	3	2	6

<sup>1</sup> Only in material next to metal mold.

<sup>2</sup> In metal left after removal of drossy material from inside of wall; outside outline = 3.

<sup>3</sup> Tool cost and cost per casting depend on number of patterns per plate or impressions in die; the more castings can be made at one operation, the lower the labor cost per piece, with inversely increasing tool cost. Sand and plaster of Paris patterns lend themselves more economically to multi-impressions than metal molds.

The numbers given are in order of preference (1 being best, 2 next best, and so on) and are self-explanatory except for the qualitative indication of strength of material. This property should be considered in conjunction with data on porosity in the same table. For instance, a cold-chamber pressure casting of a material of relatively low unit strength may have higher actual strength and certainly will be more dependable than a die casting of a material of somewhat higher unit strength, if there is the possibility of internal porosity in the die casting.

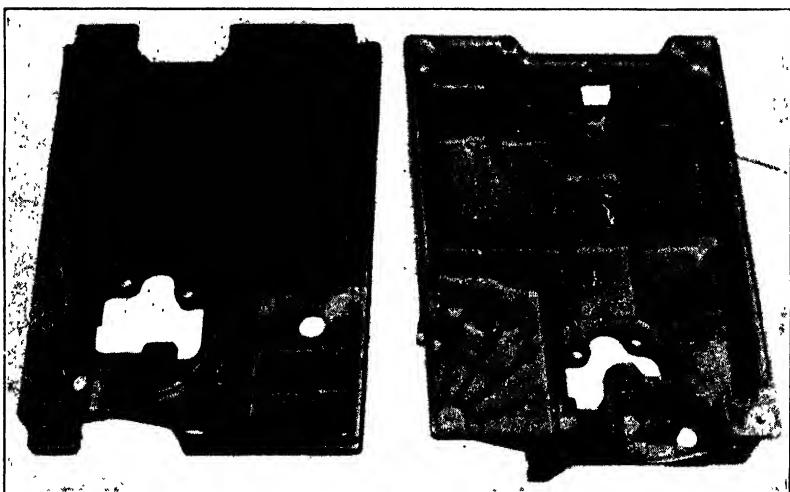


FIG. 12.30. Two views of die cast sewing machine base showing complexity, use of ribbing, etc.

Metal mold castings have higher strength, better surface appearance, and closer tolerances than sand castings of the same metal, but they entail higher tool cost. Owing to the close tolerances and good surface of metal mold castings, they usually obviate costly machining operations necessary with sand castings, except for very close tolerances. They frequently cost less than forgings requiring considerable machining, or drawn parts necessitating more than one anneal between draws, or even screw machine parts where much of the material is lost in machining.

The question of plastics versus metal mold castings cannot be covered in detail here, but the following general statements will aid in evaluating the metal mold castings.

Die castings and cold-chamber pressure castings have the following advantages:

- (a) Higher strength (tensile, compression, bending, impact, and creep).
- (b) Higher temperature resistance.
- (c) Greater electrical and heat conductivity.
- (d) Better dimensional accuracy.
- (e) Lower die cost (original and maintenance).
- (f) Higher rate of production.
- (g) Larger variations in section thickness possible.

Plastics have these advantages:

- (a) Less weight (except magnesium castings).
- (b) Better smoothness and appearance of surface.
- (c) Color, gloss, transparent and translucent effects.
- (d) Electrical insulating properties.
- (e) General corrosion resistance.

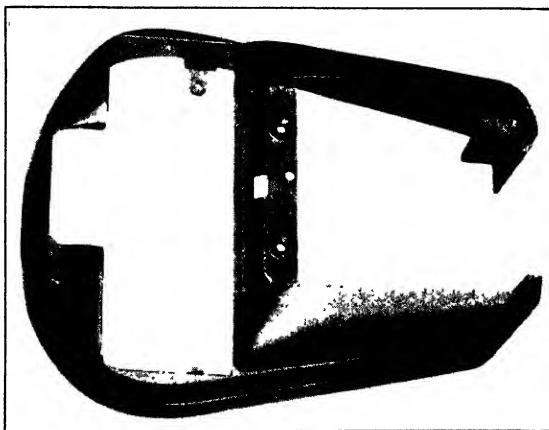


FIG. 12.31. Cold-chamber pressure casting of magnesium alloy for business machine housing. Note thin sections and fine surface finish.

Metal mold castings should be considered in every case where production is high or even moderately high (in one case, zinc die castings with a yearly production of 150 have cost less than machined gray iron castings), and where the mechanical requirements are not beyond the possibilities of this type of casting.

The length of time allowed for liquidation of tools — that is, for cancellation of the tool cost out of the savings effected in the manufacture of the finished part — varies with the job. If the order is not likely to be repeated, the period should be the life of the order. For a standard

part, the period should depend on the prospective life of the design and on the engineering and advertising advantages derived from the use of the process.

Even after the economic and mechanical advantages of one or another form of metal mold process have been definitely established, the designer should make sure that the design is definitely settled and not subject to early change due to shifting sales sentiment or to service troubles. The heavy investment in mold cost is likely to militate against an otherwise highly desirable change, or at least to load the development account unduly.

The design should be laid out for the selected form of metal mold, but if there is any uncertainty about the stability of the design, it is advisable to handle production during the introductory period with sand castings or in some other less restricting form.

Metal mold casting has been in commercial existence for only 40 years, but already great possibilities have been indicated and great developmental strides have been taken. Undoubtedly there will be new advances obsoleting in some cases the methods presented in this chapter, but certainly these methods of production have reached a position of importance in manufacturing which may be expected to continue in the post-war era.

#### REVIEW QUESTIONS

1. The following terms are used in reference to sand molds. Describe the part to which they refer. (a) Cope, (b) drag, (c) cheek, (d) sprue, (e) gate, (f) riser, and (g) core.
2. Name and describe the three classes of molding operations. What is the main difference between them? What type of equipment is used with each?
3. What is the difference between dry sand molds and green sand molds? What are some of the advantages and disadvantages of each? Why is "skin drying" employed with some green sand molds?
4. Name some of the factors which favor making a pattern of wood instead of metal. What advantage is gained through use of a match-plate pattern instead of a single (split) loose pattern?
5. Who is normally responsible for choosing the type of pattern and its design? Explain why the designer should indicate locating points on the drawing. What type of partings are preferred? How will the patternmaker normally add draft to the pattern if no engineering instructions are given?
6. What three main characteristics of solidifying metal have an important influence on the soundness of castings? Name the two kinds of defects attributable to poor design.
7. Hot tears can be prevented by eliminating hot spots and stresses, particularly concentrated stresses. Name and explain three design rules which accomplish these purposes. How can contraction cavities be prevented?

8. What is directional solidification? How may it be controlled to produce sound castings?
9. How may the soundness of a finished casting be tested without destroying the casting? What two methods are used to detect surface cracks?
10. How do the strength, surface finish, accuracy, and tool cost of plaster of Paris castings compare with sand castings? With metal mold castings?
11. What is the "lost wax" process? Name two industrial applications for this process.
12. Name the four classifications of metal molds. How do permanent molds differ from semipermanent molds? How do the castings made by each process compare? What are slush castings and what characteristics do these castings possess?
13. In what way does the die casting process differ from cold pressure casting? Describe the two types of die casting machines in common use. Name the metals and alloys cast in each type of machine and explain why they are so cast. What characteristics do die castings and cold pressure castings have in common? Why may some die castings (and, to a lesser extent, cold pressure castings as well) blister when heat treated?
14. What contributes to shrink holes in die castings? What rule of design should be followed to avoid shrink holes?
15. What types of parts may be produced by centrifugal casting? Name some of the advantages and limitations of the process.
16. Compare metal mold castings, as a class, with sand and plaster of Paris castings, and describe the design conditions under which they are most favorable.

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## CHAPTER XIII

### POWDER METALLURGY

By F. C. KELLEY, W. A. REICH, and C. D. MACCRACKEN

Strange as it seems, powder metallurgy dates back before 3000 B.C., when man first attempted to work with metals, and yet the same subject 5000 years later caused Dr. W. R. Whitney<sup>1</sup> to state, "There is a big field. We haven't yet scratched the back of powder metallurgy."

**13.1. Powder Metallurgy Defined.** Essentially, powder metallurgy is the art of producing a metallic part from powders of a single metal, of several metals, or of a combination of metals and nonmetals. It consists of the successive processes of mixing the powders mechanically, compacting them at high pressures into a preliminary shape, and heating them at elevated temperatures, but below the melting point of the major constituent. Diffusion causes the particles to unite into a single, strong, smooth metallic part much like the same composition produced by melting the various constituents together.

Powder metallurgy divides naturally into two main industrial uses: (1) Powder metallurgy parts produced by high production methods are now able to compete in the field of structural parts with conventional methods of fabrication. (2) Powder metallurgy enables materials and parts to be made that would be impractical or even impossible by any other method.

**13.2. Powder Metallurgy for Structural Parts.** Successful use of powder metallurgy for producing structural parts in competition with other methods of production requires on the part of the designer an appreciation of the advantages and disadvantages of the powder metallurgy method. Such an appreciation will guide the designer to incorporate as many of the advantages and as few of the disadvantages as possible. Some of the important advantages of the process are as follows.

**ADVANTAGES.** (1) *Elimination of Scrap.* Only the required amount of material is involved throughout the entire manufacture. By conventional methods the scrap may run as high as 70 per cent.

(2) *Elimination of Machining Operations.* After the part comes from the heating, or "sintering," process, the most that is needed is a

<sup>1</sup> Founder of the General Electric Research Laboratory.

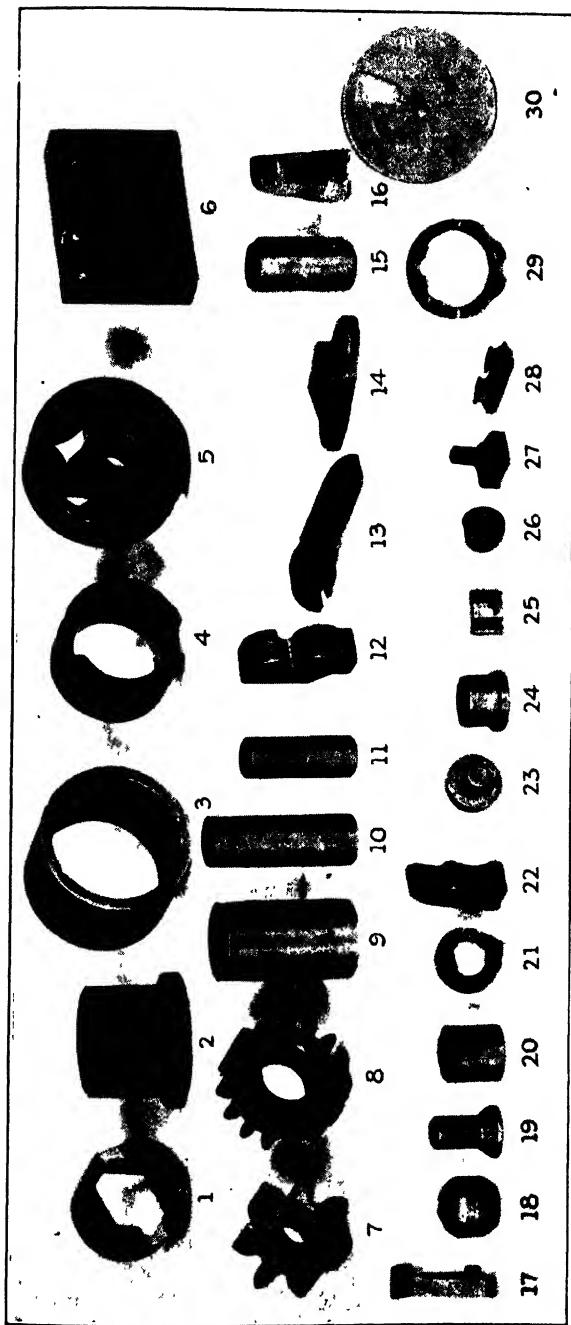


FIG. 13.1. Miscellaneous parts made from pressed powders. (View approximately 40 per cent actual size.)

- 1, 3, 9, 10, 11, 18, 19, 20, and 24. Bronze bearings and bushings of the self-lubricating type.
- 2 and 4. Lubricant-carrying bushings made from iron powders.
- 5 and 7. Automotive oil-pump iron parts.
6. Block composed of alternate layers of compressed iron and bronze.
8. Lubricant-carrying iron gear used in an electric washer.
- 12, 21, 23, 25, 27, and 30. Miscellaneous parts made from mixtures of copper and tin powders.
- 13, 14, 16, 17 and 22. Iron dovetails and brackets, chiefly automotive.
15. Lubricant-carrying spline bearing made from iron powder.
26. Porous-bronze cone used as an oil filter, to replace one of ceramic materials.
28. Cutter for G-E Disposall unit. Made of C. & bolo<sup>®</sup> powder.
29. Bronze bearing race.

simple "sizing" operation. Thus such difficult machining operations as slotting a square hole or finishing a sunken surface are avoided. The dimensions are accurate, the edges are sharp, and the surfaces are smooth.

(3) *Suitability to Mass Production.* The pressing, or "briquetting," operation consists of but one stroke of a press at a speed of up to 30 strokes per min., and the sintering operation can process many hundreds of parts in one heat. The temperature required is less than the temperature for casting. Thus high quantity production is relatively easy, the time per part is further reduced, and labor costs are cut to a minimum.

(4) *Better Control of Composition.* The nature of the process insures that the exact desired proportions of the various metal powders in the finished product can be consistently reproduced in a uniformity of composition unapproachable by foundry methods. The metal powders decrease the impurities introduced by conventional methods. Also the sintering atmosphere can be accurately controlled. In this way the product can be kept under more exact control.

**DISADVANTAGES.** However, there are disadvantages, some which are inherent in the process and some which may be reduced by further research.

(1) *High Cost of Dies.* Since pressures of the order of 30 tons per sq in. are used for briquetting, the wear on the dies is high, and large, powerful, expensive presses are required. The original costs of dies are comparable with mold costs for plastics. In order to be competitive, orders of at least 10,000 parts are needed to liquidate these expenses.

(2) *Lower Physical Properties.* (a) The tensile strength is usually not as great as that of the same material in the cast condition. (b) The impact values are usually much lower. (c) The indentation hardness is lower because sintered products are porous (the porosity ranges from 5 to 50 per cent) and thus have not the full density of wrought materials. Indentation hardness is not of as great importance for powder metallurgy parts as the hardness associated with wear resistance. Parts have been made which have very good wear resisting qualities.

(3) *Higher Cost of Raw Materials.* The cost of metal powders suitable for present-day products made by this process is several times that of metal used for making wrought material. Often, however, this raw material is more readily available since steel scrap or other by-products from metal working operations are a satisfactory source of metal powders. The cost of manufacturing these powders is steadily being reduced by research, experience, and higher quantity production.

(4) *Limitation on Design of Part.* The area of the piece directly determines the required size of press. Few manufacturers have avail-

able automatic high-speed presses having over 80 tons capacity. If pressures of 30 tons per sq in. are used, the size of part is thus limited to less than 3 sq in. of cross-section normal to the direction of pressing, but cost considerations reduce the desired size still further.

Powders when pressed do not flow around corners as do plastic materials, nor do they transmit pressures like a liquid. Because of this, the design of the part being formed is very important, especially when high briquetting pressures are used. A cast part, in order to be made by powder metallurgy, is likely to require redesign. The design features will be discussed at the end of the chapter.

(5) *Limitations as to Material.* Only four basic compositions of powder metal are now commercially available on a large scale for structural parts. They are iron, iron-copper, copper, and copper-tin. Brass and carbon steel are in limited production, and other compositions will undoubtedly make their appearance when sources of powder and production routines have been developed.

In summary, whenever a small metal part, having low service stresses, is to be produced in large quantities, the designer should definitely investigate the economics and design possibilities of powder metallurgy.

**13.3. Special Applications of Powder Metallurgy.** The second of the main industrial uses of powder metallurgy noted in Sec. 13.1 is the better known of the two because of the myriad uses and trade names that have become prominent. These products, and other great inventions that are sure to come, would not have been made possible without this process.

(1) *Ductile Tungsten.* Owing to the very high melting point of tungsten, it cannot be melted, cast, and worked as can iron or steel, since there are no furnaces or ceramic materials which could be used in such processes. Dr. W. D. Coolidge<sup>1</sup> developed a process whereby he pressed, sintered, and resintered tungsten powder gained from a reduction of tungstic oxide in hydrogen. The resulting bars when white hot could then be swaged and drawn through diamond dies to form a strong, ductile wire which is now used as the filament in all incandescent lamps.

(2) *Oil-Impregnated Bearings.* Based upon the fact that parts made from metal powders can be varied from 5 to 50 per cent porosity, engineers have used them as bearing materials containing their own lubricating oil within the pores of the metal. Pressed and sintered powders (mainly iron or bronze) have been very widely used as self-lubricating parts for oil-pump gears, door catches, cams, washers, bearings, guide blocks for machine saws, and many other articles. This field is very attractive since high production is required, automatic machinery

<sup>1</sup> Director of the General Electric Research Laboratory.

can be used, and porosity not only need not be reduced but must be retained.

(3) *Cemented Carbides.* Because of its hardness and toughness, cemented tungsten carbide invented in Germany is now widely used throughout the world for tools for machining cast iron, steel Bakelite, hard rubber, and many other materials which cause rapid wear of high speed steel tools. After preliminary sintering, it acts like a hard gray chalk and can be easily cut and shaped to the desired size. But after the final sinter, during which it shrinks about 20 per cent, it becomes too hard to work by ordinary methods.

(4) *Permanent Magnet Materials.* Aluminum, nickel, cobalt, and iron make excellent permanent magnets when combined through powder metallurgy. Although the cast alloys are brittle and have low impact resistance, the sintered material is strong with a relatively high resistance to shock.

(5) *Metal Filters.* In Diesel engines, where fuel injection pressures sometimes reach 25,000 lb per sq in., the slightest particle would clog the tiny injector orifice. This filter problem has been solved by using a powder metal part. Variations in porosity make possible almost any desired degree of filtering. The applications for this filter are rapidly increasing.

(6) *Mixtures of Metal Powders and Others Materials.* It has been found that nonmetals can be pressed and sintered with metals to form materials with new properties. Diamond impregnated cemented carbide has been developed for oil well drills and grinding wheel dressers. Graphite has been added to powdered iron for better bearing properties. At high enough sintering temperatures, iron and graphite form steel. The possibilities for invention in this field are enormous.

(7) *Other Alloys.* Copper and silver have been added to tungsten to form a high melting point alloy with high conductivity. Nickel has been sintered with molybdenum or tungsten to weld with nickel to form thermocouples for use up to 2500 F. Sintered stainless steel can also be made.

**13.4. The Manufacturing Process in Powder Metallurgy. *The Production of Metal Powders.*** Metal powders are made by several processes: (a) Reduction of oxides of the metal to a powder by means of carbon or hydrogen atmospheres; (b) electrolytic deposition at high current densities, and subsequent grinding; (c) condensing a metallic vapor to a powder as in the carbonyl process; (d) atomizing to a powder by entraining liquid metal in an air jet; (e) melting and atomizing metal wire by high velocity burning gases as in the Schoop process; and (f) most important of all, grinding of cast pellets.

*Briquetting.* After the required amount of metal powder has been mixed and placed in the die, a plunger compresses the powder under pressures up to 100,000 lb per sq in. with a compression ratio (loose filled volume to compressed briquette volume) ranging from 2 : 1 to 6 : 1. This operation is known as "briquetting" because the powder is squeezed together into a briquette. Partick shape and size distribution must be taken into consideration by the manufacturer. Speed of pressing, die wear, etc., naturally limit the pressures which can be used economically. Also it is interesting to note that the density is not noticeably increased as the pressures exceed 100,000 lb per sq in.

*Sintering.* After pressing, the briquette is heated in a furnace at a point below the melting point of the major constituent; sometimes a component with a lower melting point will become liquid. During this sintering a process of diffusion welds the adjacent particles together.

In sintering, shrinkage may occur. This is increased by higher temperatures and lower briquetting pressures. Some metal powders shrink more than others. As a result, the tolerances of sintered parts are generally on the order of  $\pm 0.001$  in. per in. in the plane perpendicular to the direction of pressing and about  $\pm 0.005$  in. in the other plane. The normal procedure includes an inexpensive "coining" operation, but closer tolerances can be obtained by additional cold pressing and "sizing" after sintering.

The powder metallurgist must take great care to prevent oxidation of the metals during sintering. Air trapped in the mass is also a great source of trouble.

*Hot Pressing.* To reduce the pressures needed in briquetting and to help eliminate uneven sintering shrinkage, heating of the dies or the part has been attempted to make the powders somewhat plastic. It was also hoped that superior strength, hardness, and impact properties might be obtained. But so far, except for special cases, economic considerations and great technical difficulties have discouraged use of this technique.

**13.5. Mechanical Properties and Design.** The physical and mechanical properties of a sintered part depend on the composition of the powder mixture; the grade of powders used; the temperature, time, and atmosphere of sintering and resintering operations; and the density, resulting from briquetting, sintering, and sizing operations.

The tensile strength, impact strength, hardness, and ductility of a metal-powder product all increase with increasing density of the product provided the same powder mixture, quality of powder, and sintering treatment are used. At present, to get high density the part must undergo additional shrinkage. So there is an unhappy com-

promise required between high strength and close tolerance. (See Fig. 13.2.)

Until design data are better known and coordinated, the only way to

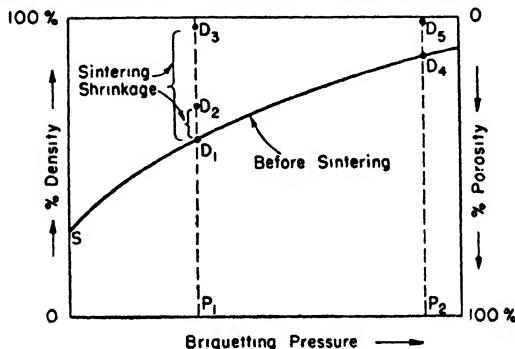


FIG. 13.2. (a) Briquetting takes place from start,  $S$ , to density,  $D_1$ , and pressure  $P_1$ . Sintering increases the density to  $D_2$  (which is desirable for porous bearings) or longer and more careful sintering may increase the density to  $D_3$  with an accompanying large shrinkage.

(b) To obtain a high density (and thus good physical properties) without great shrinkage, briquetting may continue to density  $D_4$  and pressure  $P_2$ . This procedure requires only a small volume change to  $D_5$  during sintering, but involves much greater expense.

determine the serviceability before involving the high cost of making a die for a sample part is to machine a part from a blank of the required composition.

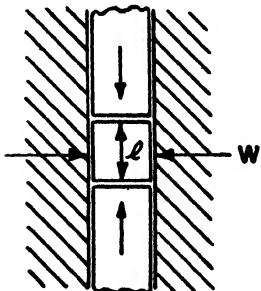


FIG. 13.3. Diagram showing length,  $l$ , and width,  $w$ , of briquette formed between punch and die walls. Decreasing  $l/w$  increases the density.

The uniformity of density is one of the most important features for the designer to consider. The density of pieces of different size and shape will vary even with identical briquetting and sizing pressure. This is because the pressure is usually applied along only one axis. Thus the density will be affected by the friction between powder and die in two ways: (1) If the ratio of  $l/w$  (as shown in Fig. 13.3) is low, the density will be greater. (2) If the ratio of  $l/w$  is high (in general greater than 2), the density distribution will be uneven. If pressed from both ends, the density will be low in the middle. If pressed from one end, the density will be low at the opposite end. (See Fig. 13.4.)

When the length,  $l$ , varies across a given piece, the density will be greatest where  $l$  is small. To get uniform density distribution in this

case, more than one punch may be needed (Fig. 13.5). Multiple punches increase the expense and should be required only when the mechanical properties of the piece are important.

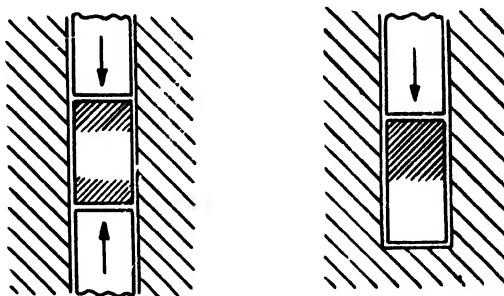


FIG. 13.4. Diagram showing the uneven density distribution caused by a relatively large  $l/w$  in pieces briquetted from one or both ends. Shaded area is the region of higher density.

Certain special shapes, such as irregular curves, eccentrics, radial projections, recesses, irregular holes, keyways, flat sides, splines, and square holes are very easily made by powder metallurgy. Tapered holes and counterbores are easily produced, but in tapered holes a short

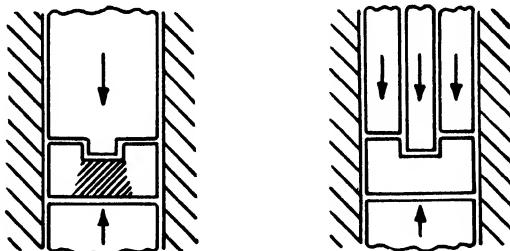


FIG. 13.5. Diagram showing the need of multiple punches in order to get a uniform density distribution with a nonuniform section. Single punch at left produces dense region (shaded area) directly under the punch. Three punches at right give more uniform density.

length at the small end should be cylindrical. Projections should not be more than one-fourth the length of the part. Also obtainable are slots, grooves, and blind holes.

Although some applications have been developed in which inserts are successfully used in pressed and sintered parts, inserts generally cannot be employed.

## REVIEW QUESTIONS

1. What are the two main industrial uses of powder metallurgy?
2. Why is low porosity desired for some metal-powder parts and considerable porosity desired for others?
3. List three advantages and three disadvantages of using powder metallurgy for structural parts.
4. List four special applications of powder metallurgy.
5. How can high density be obtained without high shrinkage? Why is this not always done when high density is required?
6. Why are multiple punches sometimes necessary?

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## CHAPTER XIV

### HOT WORKING PROCESSES

**14.1. Mechanical Working of Metals.** The purpose of mechanically working a metal is to change its dimensions, properties, and/or surface condition. Working above the recrystallization temperature but below the melting or burning point, as discussed in Chapter I, is termed *hot work*. When the working takes place below the recrystallization temperature, it is termed *cold work*.

In general, the hot working operations have the following characteristics:

(a) They refine the coarse grain structure of castings or ingots, and make the metal more homogeneous. Fine grain structure is desirable in parts for structural applications since it promotes good strength and ductility (see Chapter VI). The finishing temperature is often close to the upper limit of the cold working range so that little grain growth can occur after working, and the finest grain size will be produced. With large steel shapes or intricate designs, good plasticity is needed and a high finishing temperature might therefore be required; subsequent grain refinement would then be obtained by heat treatment.

(b) Hot working processes require less power than cold working operations for the same job.

(c) The exposure of the heated metal to the air frequently causes scaling. On many parts, this may not prove a disadvantage, but it does make it difficult to obtain close tolerances and good finish without incorporating some descaling operation such as blasting or pickling.

By comparison, the cold working operations are used in preference to or subsequent to hot working to take advantage of the closer tolerances and better finish that they make possible. They also cause a considerable increase in the strength and hardness, and a reduction in the ductility of annealed metals. These properties result from grain distortion, i.e., work hardening (see Fig. 14.1), and are important to many products such as springs, cutlery, and shell jackets.

This chapter covers the hot working processes: rolling, extrusion, hammersmithing, drop forging, machine forging, and hot pressing. Cold working processes such as stamping, forming, shell drawing, and cold heading are discussed in Chapter XV.

**14.2. Hot Rolling.** Hot rolling consists in compressing and lengthening a piece of metal as it is fed between two rolls rotating in opposite directions. The flow of metal is continuous and almost entirely in a longitudinal direction. Plate, sheet, and strip are commonly rolled between plain cylindrical rolls, but structural shapes (angle iron, chan-

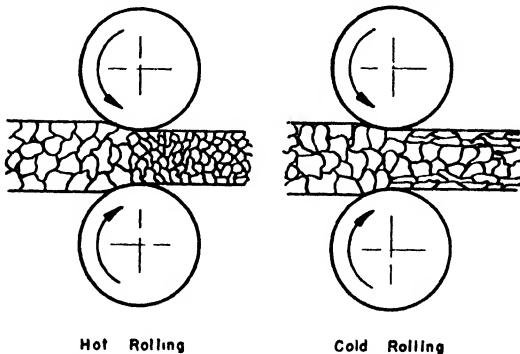


FIG. 14.1. Hot rolling refines, while cold rolling distorts grain structure.

nels, etc.), rails, and many rods and bars are produced by successive passes through rollers grooved to give the desired shape. The materials commonly rolled include aluminum, magnesium, copper, steel, and many other alloys.

When close tolerances are placed on the size of the parts, or a good surface finish is required, a cold rolling operation may follow preliminary shaping by hot rolling.

**14.3. Pipe and Tube Production.** Steel strip and plate which are rolled to the proper size for making pipe are called *skelp*. This skelp

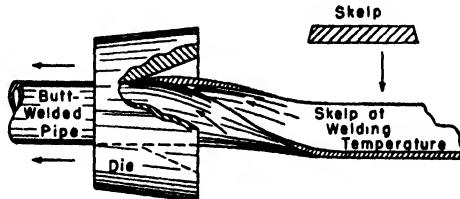


FIG. 14.2. A common method of curling and butt-welding pipe.

has the edges rolled in such a way that they meet in either a butt joint or a lap joint when bent into a tube before welding. Butt-joint welds cannot stand as high pressures as lap-joint welds but are satisfactory for many types of service. Butt-welded pipe is made in sizes  $\frac{1}{8}$  in. to 3 in. in diameter. The most common method of butt welding is shown in Fig. 14.2. The skelp is heated to welding temperature and

drawn through a bell-shaped die. The die curls the skelp into a tube and forces the edges of the seam together, causing them to weld.

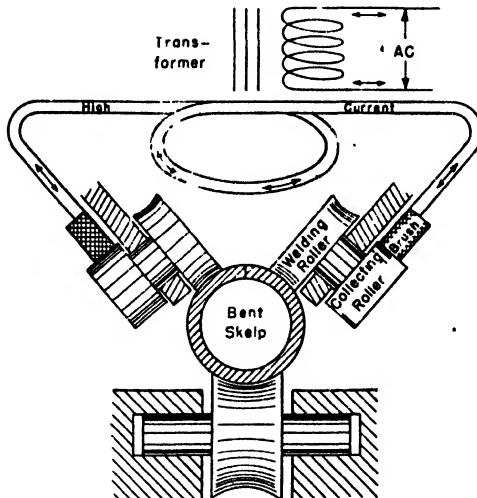


FIG. 14.3. Butt welding pipe seam by electrical resistance method.

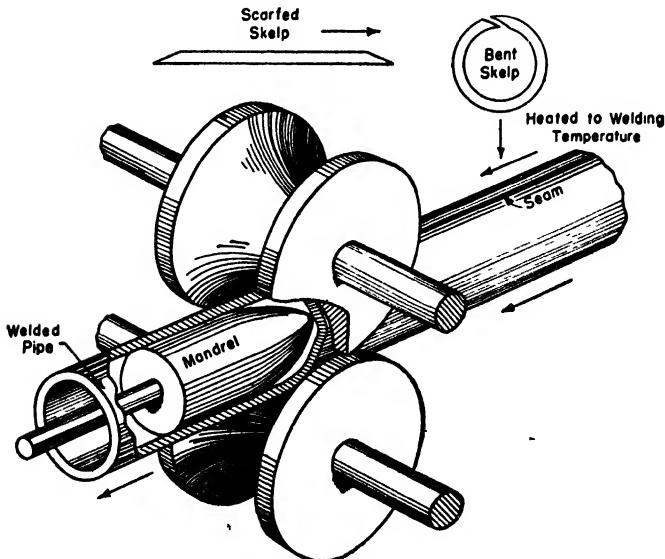


FIG. 14.4. Lap welding by rolling seam over mandrel.

Another method which is coming into common use is shown in Fig. 14.3. The skelp is first bent into a tube, either by drawing it through

a bell die, or, for large sizes, by rolling it sideways in a set of bending rolls. The bent skelp is then passed between two electrified rollers which carry enough current to heat the seam to its welding temperature.

A lapped seam cannot support itself in compression so the simple method of Fig. 14.2 cannot be used for lap welds. The original bending of the lap weld skelp is accomplished in a bell die or bending rolls, and then it is passed over a mandrel between rollers as shown in Fig. 14.4. The mandrel is firmly held between the rolls, and a good weld is obtained. Pipe 25 ft long and 1 $\frac{1}{4}$  to 26 in. in diameter is made by this lap welding method.

Most seamless tubing is made by piercing a hot steel rod as shown in Fig. 14.5. The two large rollers running slightly askew rotate the

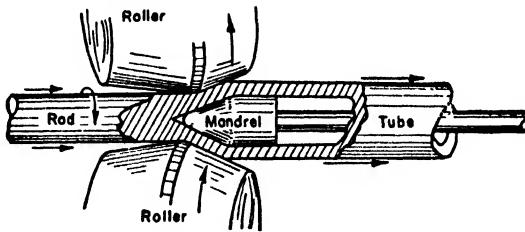


FIG. 14.5. Roll-piercing seamless tubing from solid rod.

rod rapidly and advance it slowly. The rolling action ruptures the rod at its center, and the mandrel enlarges and smooths this break. The resultant tube is usually redrawn cold to improve inside and outside finish.

**14.4. EXTRUSION PROCESSES.** In the extrusion processes, a sufficient pressure is applied to a metal billet or blank to cause it to flow through a restricted orifice, thus forming a greatly elongated part of uniform cross-section. Either hydraulic presses or mechanical presses are used to apply the necessary pressure, the process being the same for hot and cold working.

Some typical applications of this process include extrusion of metals of low melting point such as lead, tin, zinc, and lead-tin alloys for cable sheathing, hose casing, pipe, and solder wire, and extrusion of the alloys of copper, aluminum, and magnesium as rods, tubes, and both solid and hollow structural sections of small size.

In comparison with slow extrusion under continuous pressure, there are two modifications of the process in which a rapid mechanical blow is applied. These are referred to as the *Hooker process* and *impact extrusion*. The former is usually a cold extrusion process and is com-

mercially applied mainly to the production of small, thin-walled copper and aluminum seamless tubes and small cartridge cases. A cup-shaped slug of metal must be used, and it is extruded ahead of a punch through an annular orifice between the punch and a die. Impact extrusion is quite similar to the Hooker process, but the flow of metal is in the opposite direction. A flat slug of metal is placed on a solid bottom die, and the impact of the punch causes the metal to flow back over the punch, which has a uniform section, slightly relieved as illustrated in Fig. 14.6. This process is also applied primarily to aluminum, magne-

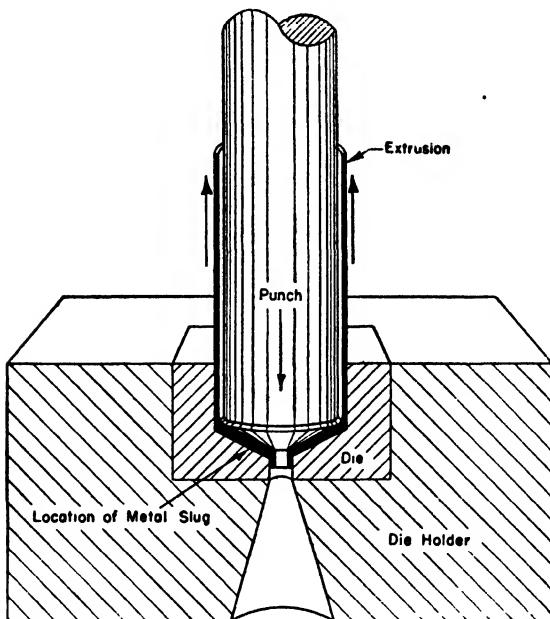


FIG. 14.6. Impact extrusion of collapsible tube.

sium, copper, lead, tin, and zinc at the present time. Some typical applications are tooth paste, shaving cream, and paint pigment tubes and fairly deep (depth  $\geq 1\frac{1}{2}$  times the diameter) shells and cams, particularly those which should have a heavy closed end containing some type of boss or section.

**14.5. Principles of Forging.** *Forging* is the term used to define the hot working of metal by a localized compressive force which is applied by the use of hammers, presses, and forging machines. Before taking up the various divisions of forging work, a few fundamentals of metal flow common to all will be considered.

*Upsetting.* A simple form of hot plastic deformation takes place when a round bar is struck axially between two flat dies. It is shortened and the metal, following the path of least resistance, spreads out (Fig. 14.7a). Owing to the friction and chilling effect of the die faces, both of which tend to prevent deformation, the flow is restricted at the die surfaces, thus producing a bulge or barrel shape. If a square bar is upset, the square cross-section is distorted as shown in Fig. 14.7b, since the resistance to flow is less at the middle of the sides than

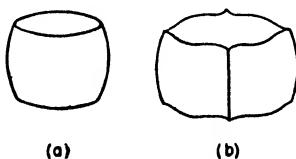


FIG. 14.7. Bars upset between flat dies.

at the corners. The bulge at the center between die faces is present as before.

*Edging.* Edging is performed as shown in Fig. 14.8. Here the metal is displaced to the desired shape by striking it between two dies (Fig. 14.8a and b). As the dies strike the stock (Fig. 14.8c), metal is gathered

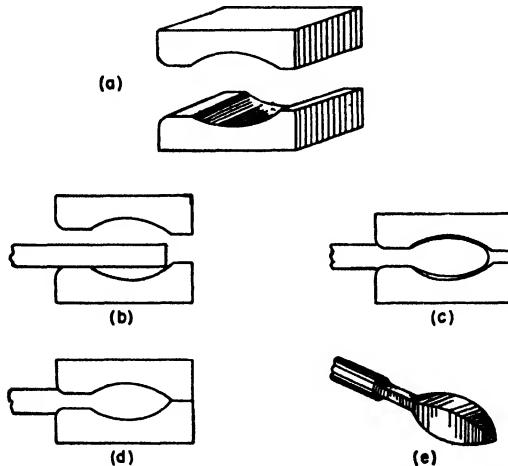


FIG. 14.8. Edging.

toward the center of the cavity and some sidewise movement also takes place. The action is shown completed in Fig. 14.8d. By turning the stock 90 degrees and restriking, a section enlarged over the stock diameter in two directions is produced (Fig. 14.8e). Edging is frequently used as a preliminary drop forging operation.

*Drawing.* In direct contrast to upsetting, drawing is a spreading, stretching, or thinning action. It is accomplished in forging by striking the work as shown in Fig. 14.9. The impact of the dies on the metal

being formed tends to reduce its thickness and increase its length and width.

*Bending.* In bending there is a thinning of the material as shown in Fig. 14.10a, accompanied by a spreading of the metal on the inside of the

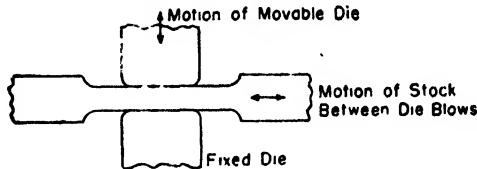


FIG. 14.9. Drawing.

bend and a narrowing at the outside (Fig. 14.10b). When quantity justifies it, bending dies may be used, but for small lots the blacksmith would perform this operation over an anvil. Bending is often necessary either as a final operation or as a preliminary step in fitting an upset and drawn metal section to the cavity of a drop forging die for the final shaping.

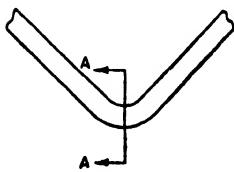


FIG. 14.10. Bending.



Section A-A

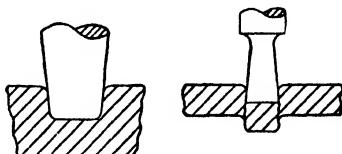


FIG. 14.11. Two methods of hot punching.

*Punching.* The usual method of hot punching is illustrated in Fig. 14.11a. A blunt tapered punch is driven about halfway through the stock, displacing rather than severing the metal. Turning the piece over, the punch is driven through from the other side to meet the first hole. Only a small slug of metal is actually cut out.

For thin metal, shearing as shown in Fig. 14.11b is usually employed.

*Confined Flow.* All of the operations discussed so far have left the metal free to flow in one or two directions while being acted upon in a third. There is a most important class of operations in which the metal is ultimately confined in all directions, being forced to behave as pasty fluid in filling every portion of the confining cavity. This is the basis of drop forging and hot pressing.

Consider the deformation of a slug of hot metal placed in a die as shown in Fig. 14.12a. As the die closes, upsetting takes place as in

Fig. 14.12b, only a small amount of metal moving into the hub cavity in the upper die. Shortly before the die faces meet, the metal reaches the outer walls of the main cavity and these exert a pressure which is transmitted, as in any fluid, throughout the metal, causing it to push up into the hub cavity (Fig. 14.12c). The quantity of metal in the slug

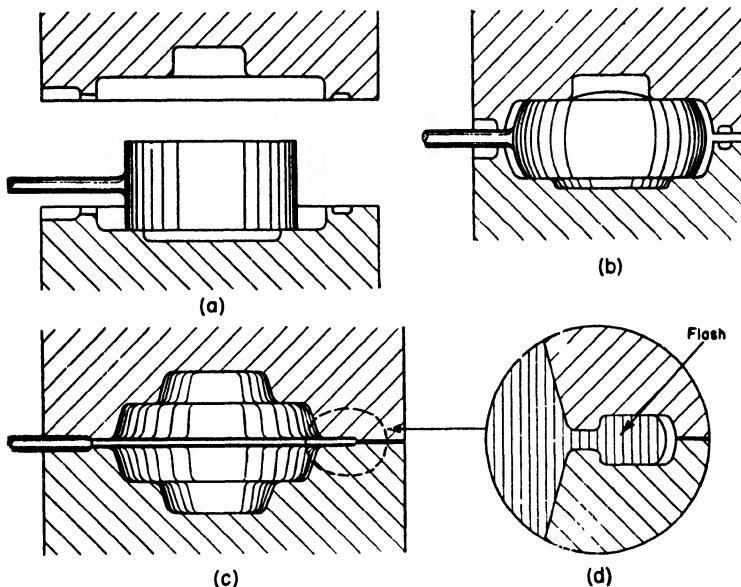


FIG. 14.12. Flow of metal in a forging die.

is calculated to be just a little more than is required to fill the die cavity proper in order to insure a well-filled shape. The excess squeezes out into an overflow region known as the *gutter*, which runs entirely around the periphery of the die cavity. In Fig. 14.12d the excess metal is shown not quite filling the flash gutter, a proper condition.

It would seem from the above that almost any shape could be produced in this manner since the metal flows as a fluid into remote cavities. But the friction against the die surfaces, and the viscous forces in the metal become much larger as the metal is chilled and as it moves into deep cavities. If too drastic deformation is attempted, flow into the flash gutter is the path of least resistance and an incomplete forging with excessive flash is produced. This difficulty can be avoided by a sufficient number of pre-forming operations which distribute the metal gradually toward its finished shape.

*Fiber of Metals.* If a hot worked part is cut in a plane aligned with the direction of working and the surface is polished and etched with a

suitable reagent, the exposed metal will usually appear to the naked eye to have a fiberlike structure (see Fig. 14.13). These fibers are really nonmetallic inclusions or segregated phases which have been elongated or "flowed" in the direction of working. Tests have shown that the tensile strength, endurance limit, wear resistance, and especially the

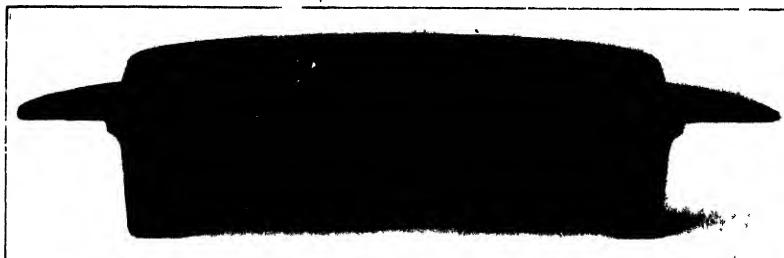


FIG. 14.13. Macrophotograph showing "fiber" lines in an etched forging.  
(Photograph courtesy A. H. Milne and Am. Soc. Metals.)

impact strength and ductility of the forging are quite superior in directions parallel to these fibers than across the fiber. The metal is thus much like wood in its directional properties, but not so marked. By properly working the metal, it is possible to obtain a fiber distribution which is most favorable for a part to withstand its service stresses.

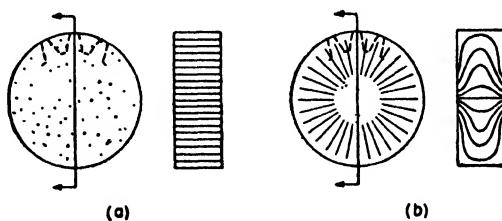


FIG. 14.14. Direction of grain flow in a gear blank; (a) bar stock and (b) forged stock.

For example, consider a gear blank machined out of bar stock (Fig. 14.14a). The fiber is uniformly axial, but the primary service stress on the gear teeth is tangential. By upsetting a slug as shown in Fig. 14.14b, the fibers are bulged radially, producing a fiber pattern such that the stress is not placed across the fiberlike inclusions during the bending of the teeth.

**14.6. Forging Metals.** Practically all metals of industrial importance can be forged successfully, but there is some difference between metals in the ease with which this can be done. Among steels, the low-carbon

ones are the easiest to forge. Increasing the carbon or other alloying elements makes forging somewhat more difficult and also increases wear on dies.

Aluminum, magnesium, copper, and forging brass are readily forged. High-alloy bronzes, Monel metal, and other strong nonferrous alloys compare with the mildly alloyed steels in forging difficulty and die wear.

**14.7. Hand Forging.** Hand forging is applicable where relatively small quantities of parts are required and where the mass involved can be heated, forged, and handled by the blacksmith and his helpers. Generally speaking, the accuracy and intricacy obtainable are less than that of drop forging.

Hand forging has largely been replaced by the various kinds of power forging but it is still extensively used for repair work, particularly in the railroad industry. Among the jobs which can be done by hand forging are making and repairing crane chains, hooks, etc., bending turbine diaphragm outer rings, and making lathe and planer type cutting tools.

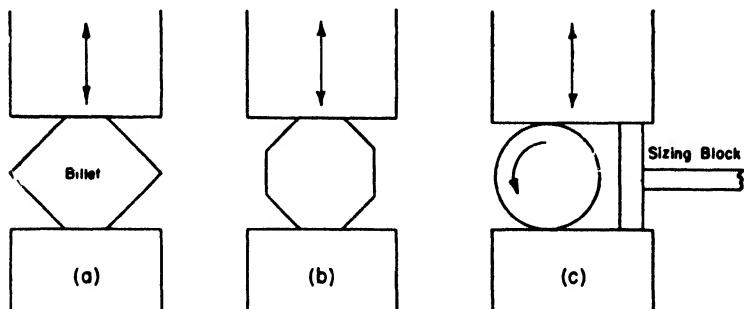


FIG. 14.15. Forging a shaft from a square billet.

**14.8. Power Hammer Forging (Hammersmithing).** The work of the hammersmith has much in common with the blacksmith. In both, the smith's skill plays a very important part in the accuracy and uniformity of the work. The tools of the hammersmith are similar to those of the blacksmith except that the power hammer has been substituted for the anvil and sledge, and the other tools are increased proportionately in size.

The following typical hammersmithing jobs serve to illustrate the type of forging work which is performed with general purpose dies and tools.

**Large Motor Shaft.** A 24-in. square ingot is first rolled at the steel mills into a square billet, perhaps 12 in. on a side. In this form a suit-

able length is reheated at the forging shop and then hammered across the corners, as shown in Fig. 14.15, until the final rounding to a diameter of perhaps 10 in. is completed between hammer faces spaced by the sizing block. Reductions from 450 sq in. to less than 30 sq in. are entirely practicable by this method.

Frequently, it is more economical to stock a few sizes of material and to forge the material to the required shaft section as the occasion demands than to stock a wide variety of sizes, thus increasing carrying charges, stock space, and the payment of extras on odd shapes and small sizes.

TABLE 14.1

<i>Outside Diameter</i>	<i>Tolerance on Diameter</i>
Up to 12"	$\pm \frac{3}{8}''$
12" to 24"	$\pm \frac{1}{2}''$
24" to 40"	$\pm \frac{3}{4}''$
Over 40"	$\pm 1''$

*Flange Coupling.* The forging of a flange coupling blank is an application of upsetting and also illustrates the use of a hammersmith's semi-general-purpose tools. Fig. 14.16 shows how the stock diameter is first upset to the coupling hub diameter inside the ring, and how, with continued blows, the flange is mushroomed out, producing excellent grain flow for carrying tangential loads.

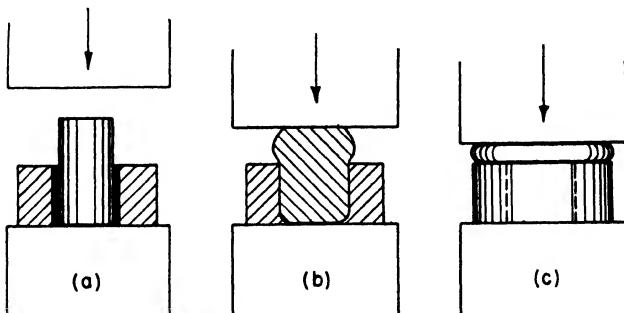


FIG. 14.16. Forging a flange coupling.

*Rings.* The operations performed in the forging of medium and large sized rings illustrate power hammer punching as well as upsetting and drawing.

Following heating and rounding up, the proper amount of material is upset until the height of the billet is about 15 per cent greater than the finished ring. A punch is driven approximately halfway through

the blank from both sides as shown in Fig. 14.17. In this way the metal is displaced from the center of the blank into the wall of a ring. Successively larger punches may be used to enlarge the ring up to 12 in. inside diameter.

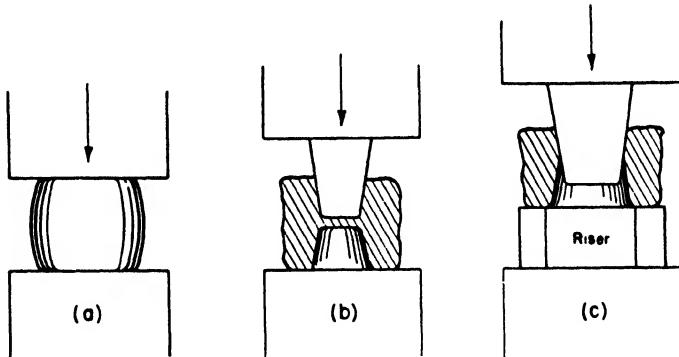


FIG. 14.17. Punching a medium sized ring.

Rings with inside diameters greater than 12 in. are generally forged over a mandrel as shown in Fig. 14.18. As the ring approaches its finished size, a mandrel is used having a radius of curvature almost as large as the inner radius of the ring.

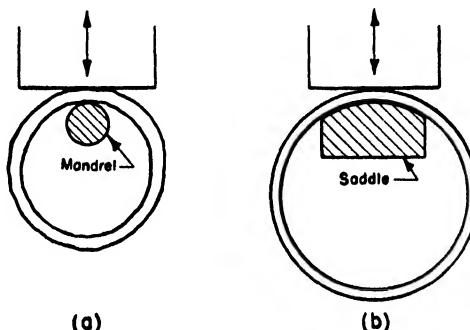


FIG. 14.18. Drawing a large ring.

Table 14.1 gives the tolerances to which ring forging can be economically held. Where more than one ring forging is required of the same inside and outside diameters, it is frequently less expensive to forge one ring of sufficient width to make two or more machined pieces than to make individual forgings.

**14.9. Drop Forging.** Drop forging is the operation in which a metal part is formed by repeated hammer blows on a bar or billet placed between a pair of dies containing the impression of the finished shape

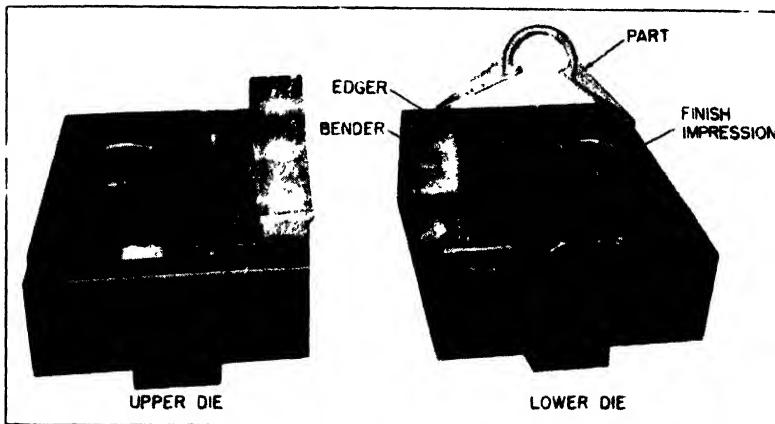


FIG. 14.19. Forging die.



FIG. 14.20. Trimming die for forging made in die shown in Fig. 14.19.

desired. Several operations, such as drawing, upsetting, and bending, may be performed in a single die. Fig. 14.19 shows a typical forging die with the several parts labeled. In this die the stock is first upset

on both ends in the edger, than transferred to the bender, where it is made to conform reasonably well to the impression. It is finally brought to the finished shape in the finish impression. Overflow into the gutter (which surrounds the finish impression) is subsequently trimmed in a die conforming to the profile of the forging at its parting line (see Fig. 14.20).

If the shape of the part makes drastic metal flow unavoidable, an intermediate or breakdown impression would be employed.

This would forge a partial development of the finished shape and would serve to protect the finish impression from excessive wear. Its smooth contours also would aid in properly filling deep recesses.

In order to prevent overheating of the die and to loosen the scale on the forging, the part should be lifted slightly between blows. This is possible only when sufficient draft has been allowed by the designer. Though it is possible to forge with a three-degree draft, seven degrees is the standard allowance and is much preferred. Lubricant applied to the impression aids in the ejection of the part and in loosening of scale by reducing sticking and by gasifying when in contact with the hot forging. The gas



FIG. 14.21. Board drop hammer. (*Courtesy Drop Forging Association.*)

pressure forces the part free of the cavity.

Before describing the operations required to produce some typical drop forgings, drop hammers and their operation will be considered. All drop hammers consist of three essential parts: a hammer or ram, a lifting device, and an anvil. The machines are classed according to their lifting device as steam, air, or board drop hammers.

The *board drop hammer*, shown in Fig. 14.21, has boards, usually of maple, assembled into the ram by means of wedges. The upper ends of these boards lie between two rollers which are controlled automatically so that when the rolls squeeze against the boards and revolve in opposite

directions the ram is lifted. At a predetermined height, the rolls are automatically spread apart. Before the ram falls, wedges lock in against the boards. When the operator wishes to strike a blow, he presses a treadle and the connecting linkage releases the wedges.

This type of hammer is generally driven directly by electric motors and requires no steam or high pressure air. It is the least expensive of the three types to operate.

The *steam drop hammer*, Fig. 14.22, has the same essential parts as the board hammer except that a steam cylinder, piston, and rod are substituted for the board lifting mechanism. The steam hammer utilizes the driving effort of the steam both on the lift and on the power stroke, resulting in a faster and more powerful hammer and one that can be better controlled. Because of its higher speed and controlled blow, the steam hammer is superior to the board hammer where preliminary bending or drawing is required. Steam hammers are also available in larger sizes than board hammers.

The *air hammer* is similar to the steam hammer in operating characteristics and construction.

It is adapted to the same classes of work as the steam hammer and is justified principally by a lower operating cost.

The following typical jobs will serve to illustrate the type of work which is normally done as drop forging work.

*Copper Switch Contact.* Fig. 14.23 shows a die for forging copper switch contacts. Three impressions are shown in this die: (1) The edger, shown at top but located at the operator's right in service (for first upset); (2) the breakdown impression (lower, the partial development of the finished shape); and (3) the finish impression (middle, note gutter around this impression).

*Crankshaft.* The various steps in forging a single-throw crankshaft are shown in Fig. 14.24. Fig. 14.25 to 14.29 are included to show some

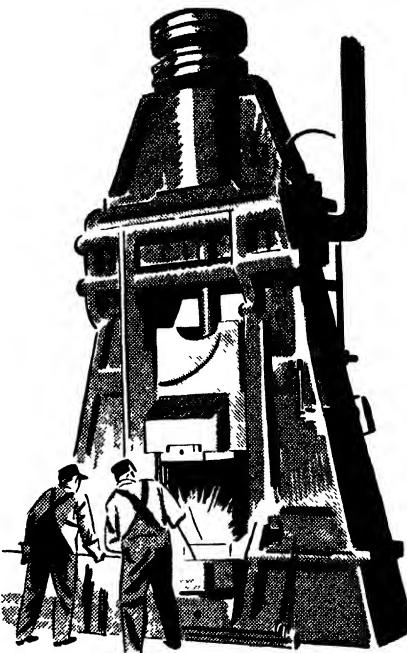


FIG. 14.22. Steam drop hammer. (*Courtesy Drop Forging Association.*)

of the actual setups. The operations are in order:

- (1) Form flange and draw tong hold (Fig. 14.24*b* and 14.25). Stock is turned in the dies between hammer strokes, to gather flange metal.
- (2) Flatten (Fig. 14.24*c* and 14.26). Done between plain flat dies.
- (3) Bend (Fig. 14.24*d* and 14.27). Done to make stock fit into die impressions.
- (4) Forge in crankshaft impression (Fig. 14.24*e* and 14.28). Bent stock is forged until chilled flash prevents further metal flow.

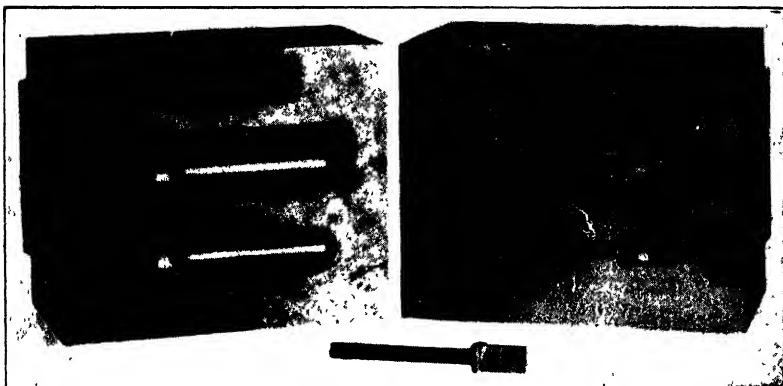


FIG. 14.23. Dies for a copper switch contact. A part made with these dies is shown in the center foreground.

- (5) Trim flash (Fig. 14.24*f* and 14.29).
- (6) Reheat.
- (7) Forge again in crankshaft impression (Figs. 14.24*e* and 14.28). Continue if necessary until shaft is reduced to drawing size.
- (8) Trim flash again (Fig. 14.24*f* and 14.29).
- (9) Restrike in crankshaft impression for final straightening and sizing.
- (10) Saw off tong hold.
- (11) Heat treat.
- (12) Shot blast.

In the forging of a shaft of this type several hammers may be necessary. Where possible, all dies are set at one time, the forging passing from furnace to hammer, back to the furnace and to the next hammer, thus saving the heat left after each preceding operation.

*Design Principles.* Certain principles relating to drop forgings that have been brought out directly or indirectly may be summarized as

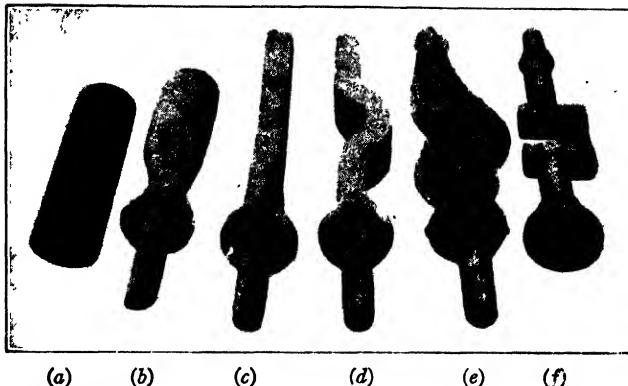


FIG. 14.24. Steps in forging a single-throw crankshaft.

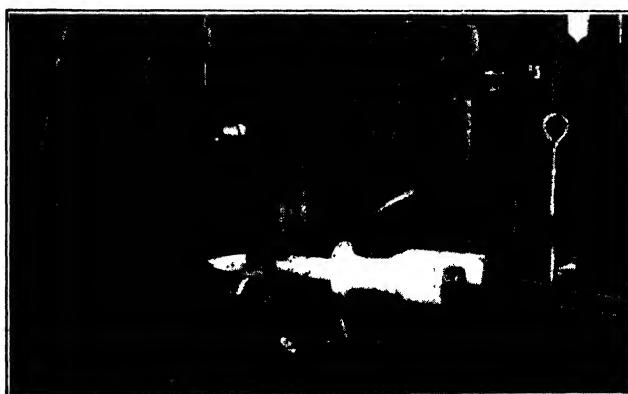


FIG. 14.25. Forming tong hold and flange.



FIG. 14.26. Drawing and flattening operation.

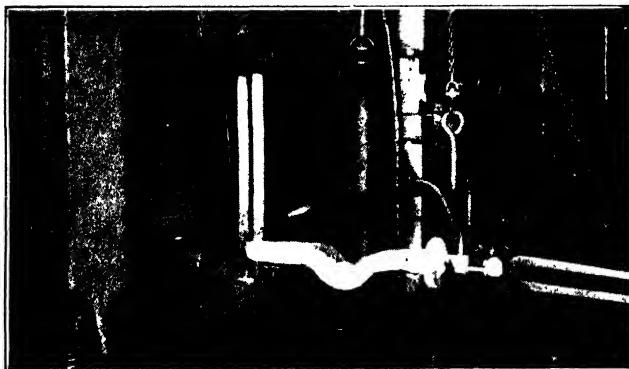


FIG. 14.27. Bending operation.

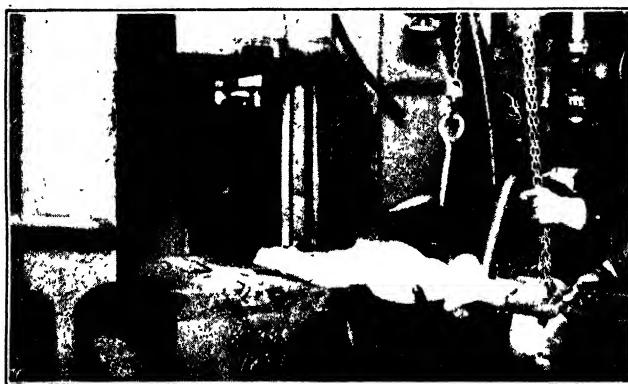


FIG. 14.28. Finish forging operation.

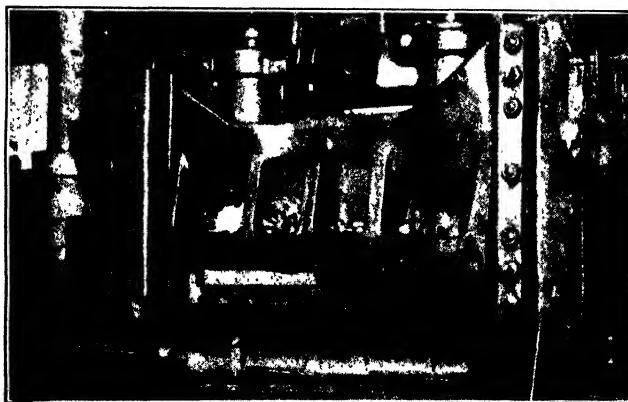


FIG. 14.29. Trimming operation.

follows:

- (1) The various sections of the forging should be balanced.
- (2) Generous fillets and radii should be allowed.
- (3) Sufficient draft should be allowed, preferably seven degrees.
- (4) Deep holes and high projections are not desirable.
- (5) Holes in two planes will make removal of the forging from the dies impossible.

**14.10. Forging Machine Work.** One of the most recent developments in the field of forging equipment is the forging machine. In it the hot work is held by stationary grips and upset by an upsetting ram or header. The machine has several grips and several corresponding positions in the header so that successive operations may be performed in sequence without requiring reheating between operations. The operation of the forging machine is primarily one of gathering or upsetting. This is to be compared with the spreading or flattening operation of the drop hammer.

Because of the spreading of the stock beyond the die impression, in drop hammer work it is occasionally necessary (for close tolerances)

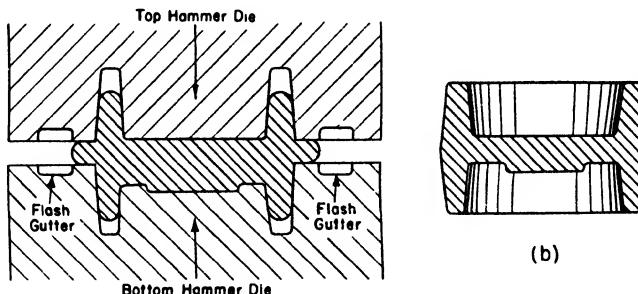


FIG. 14.30. (a) Die forging action; (b) the forged part.

to trim off the flash in order to develop sufficient pressure on the stock to cause it to fill the impression. (See Fig. 14.30.) The arrangement of the dies in a forging machine allows many types of upsets to be confined in the heading tool or between the gripping dies (Fig. 14.31), thus eliminating the intermediate trimming operations. When flash cannot be avoided, it should be located where it can be easily removed by trimming, chipping, and grinding.

The slugs of metal forged to the shape shown in Fig. 14.31b are pinched off bar stock by the grip dies as they close, the bar being inserted perpendicular to the plane of the page. After the grip dies have closed, the upsetting tool rams in, squeezing the metal to the desired shape. The

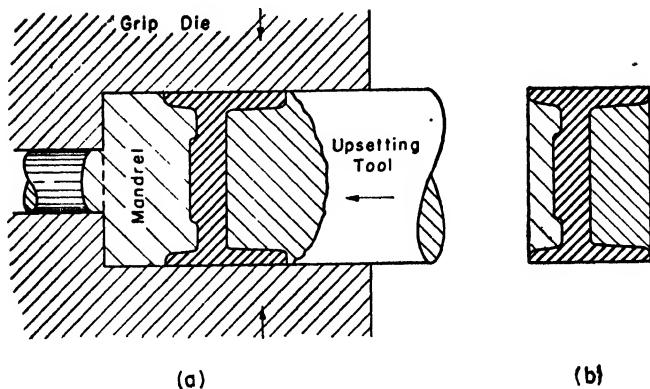


FIG. 14.31. (a) Machine forging action; (b) The forged part. Compare with Fig. 14.30.

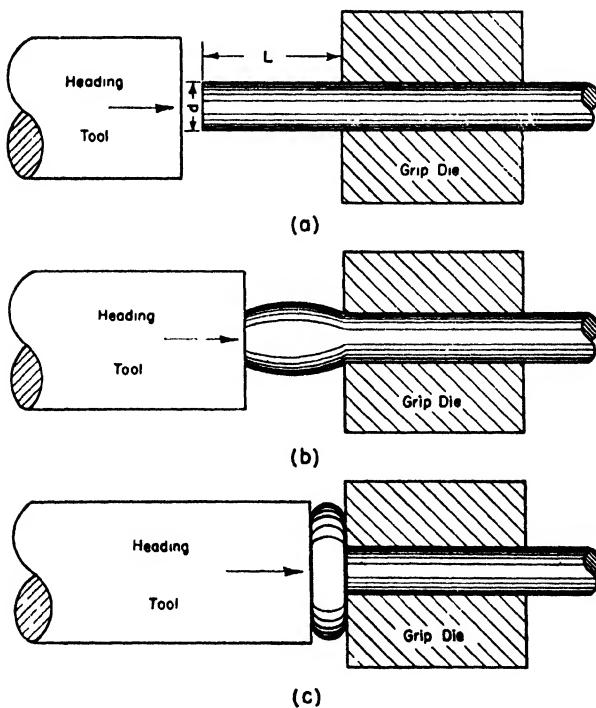


FIG. 14.32. Rule 1:  $L$  must be no greater than  $3d$ .

upsetting tool returns, the dies part, the mandrel is pushed out, and the forging is removed from the mandrel. After the mandrel is replaced in the dies, the cycle may be repeated.

*Rules for Upsetting.* Three rules which govern the proportions of most upsets made on forging machines are as follows.

(1) *The limiting length of unsupported stock that can be gathered or upset in one blow without injurious buckling is three times the diameter*

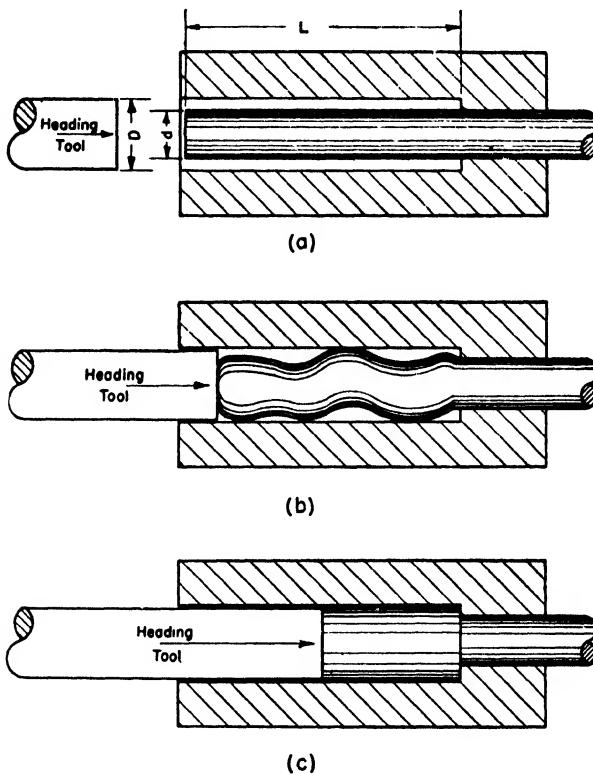


FIG. 14.33. Rule 2:  $D$  must be no greater than  $1\frac{1}{2}d$ .

of the bar. As an example (Fig. 14.32a), if the diameter of the bar,  $d$ , to be upset is 1 in., then the length of the unsupported stock,  $L$ , which can be successfully gathered cannot be more than 3 in. This rule applies to all diameters of stock. On such upsets, as the heading tool advances (Fig. 14.32b), the stock will upset uniformly in all directions from the axis of the blank. There will be no serious tendency to upset unevenly. However, if an effort is made to upset a length of stock longer than three

diameters, the stock will buckle at a point near the middle and result in a flattened bend rather than the uniform upset (Fig. 14.32c) that is desired.

(2) *Lengths of stock more than three times the bar diameter can be successfully upset in a cavity with one blow, provided the diameter of the cavity*

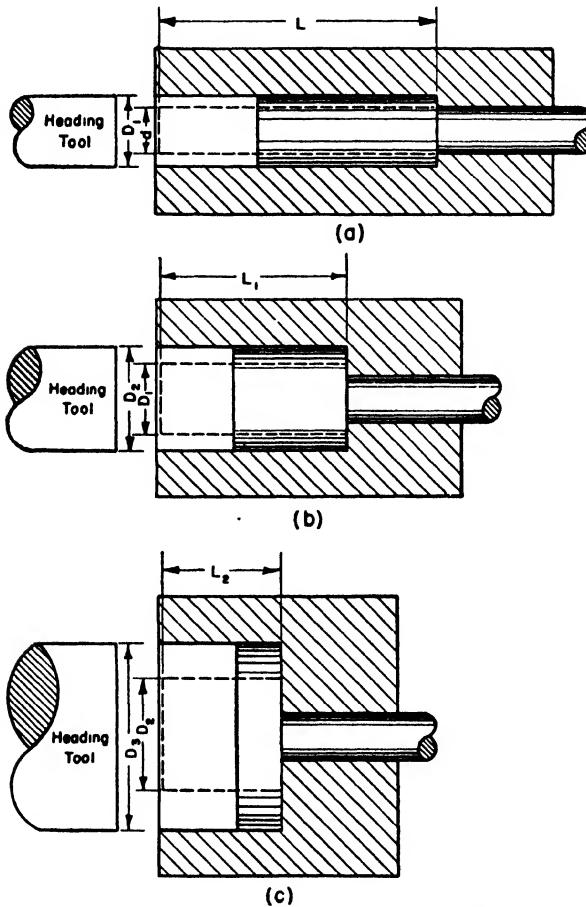


FIG. 14.34. Successive upsetting operations.

*is not more than one and one half times the bar diameter.* Assuming that the diameter of the bar in Fig. 14.33a is 1 in. and the length of stock,  $L$ , to be upset is 6 in., the diameter of the cavity in the die must not be more than  $1\frac{1}{2}$  in. When upsetting begins, as in Fig. 14.33b, the stock

will at once buckle, but because of the limited diameter of the cavity, the stock soon comes in contact with the sides of the die. This prevents

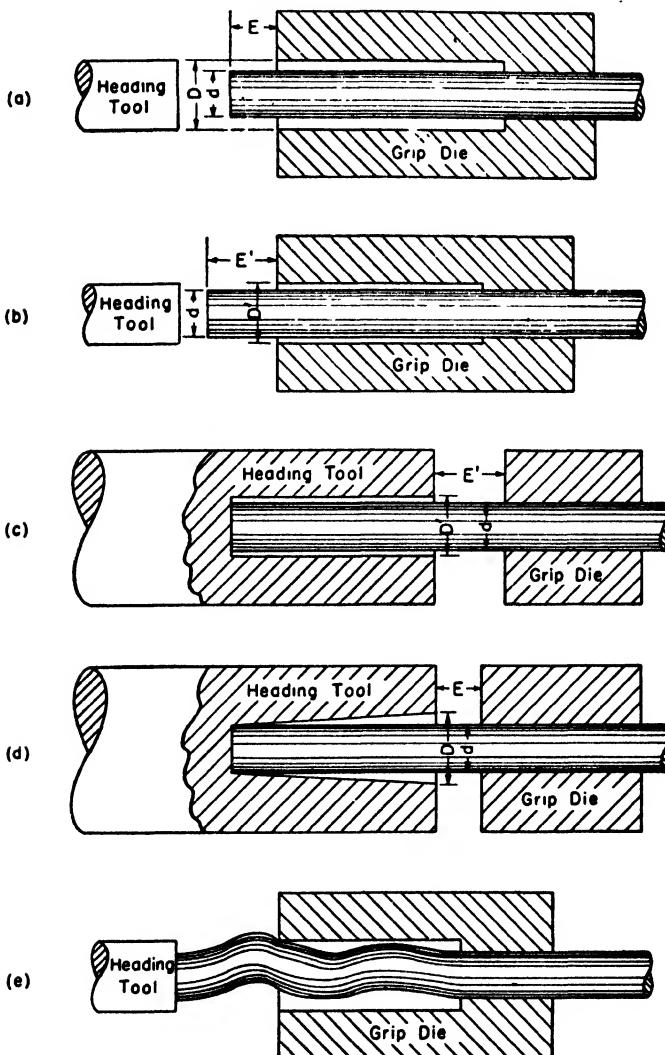


FIG. 14.35. Rule 3:  $E$  must be no greater than  $d$  if  $D = 1\frac{1}{2}d$ .

further buckling at that point, hence additional buckling must take place at some other point. As the header advances, the stock will finally upset and fill the impression.

If rule 2 is violated, fold defects are likely to occur in the upset where bending has progressed too far before upsetting began.

The practical application of this principle is in the gathering of large amounts of stock by repeating the upsetting operation, as indicated in Fig. 14.34. In the first or top impression, the diameter,  $D_1$ , of the recess in the die is not more than one and one half times the diameter of the bar,  $d$ . In the second impression, the diameter of the recess,  $D_2$ , is not more than one and one half times the diameter of the previous upset,  $D_1$ . In the last impression, the length of the upset,  $L_2$ , is well within the limit of rule 1, regarding the length of unsupported stock, so that no limit need be put on the diameter,  $D_3$ , of the last impression.

(3) *In an upset requiring stock more than three diameters in length and in which the diameter of the upset is one and one half times the bar diameter, the amount of the unsupported stock beyond the face of the die must not exceed one diameter of the stock.* For example, if the stock to be upset is 1 in. in diameter by 6 in. in length (Fig. 14.35a) and the diameter of the hole in the die is 1½ in., then the amount of stock,  $E$ , extending beyond the face of the die must not be more than 1 in. However, if the diameter of the cavity (which may be in the heading tool or the die, Fig. 14.35b and 14.35c) is reduced below one and one half diameters, the length of the unsupported stock beyond the face of the die can be increased. In Fig. 14.35b the diameter of the cavity,  $D'$ , is one and one fourth times the stock diameter,  $d$ , so the amount of stock beyond the face of the die,  $E'$ , has been increased to one and one half times the bar diameter. This rule applies to cases where the upsetting takes place in either straight or tapered cavities as shown in Fig. 14.35c and 14.35d. Should a greater amount of stock extend beyond the face of the dies, it is likely to buckle outside of the cavity as shown in Fig. 14.35e.

*Draft.* In forging machine work, as in drop forging, draft must be allowed on the faces parallel to the header motion. In general, from two to four degrees is allowed, but in some cases it may be reduced to one degree or less.

**14.11. Hot Pressing.** Hot pressing, which is now applied to ferrous as well as to nonferrous materials (copper, brass, bronze, aluminum, Monel, etc.), is a variety of the better-known drop forging process, but the material to be deformed is struck with a single, sustained blow instead of being hammered several times.

Hot pressed parts can be made more accurately, require less draft, and have fewer design limitations than drop forgings, though their size may be somewhat more limited. For such shapes as can be handled in one heat, where production is high enough to justify the forging-die cost, and where the accuracy and tolerances of drop forging are satisfactory, drop forgings will be less expensive than hot pressed parts.

**14.12. Forging as a Manufacturing Process.** Forging, as a manufacturing process, offers many advantages to both the engineer and the factory man. Among these advantages are: (1) Equal or greater strength at lower unit weight, compared to castings or fabricated parts; (2) greater consistency of performance than is possible with castings; (3) minimum of surplus material to be removed by machining.

In addition, a comparison with castings shows that drop forgings can be made to closer tolerances and an excellent surface may be had even on unfinished portions. On the other hand, dies initially cost more than patterns, and intricate shapes may not be forgeable though they could be cast. Generally speaking, the costs of drop forgings and castings in carbon or alloy steel are comparable if composition is the same for each, and if sufficiently large lots are required. Cost, however, is not usually the deciding factor in the selection between these processes.

On the foregoing pages only the general principles and methods of forging have been pointed out. It should be borne in mind that use of special materials, equipment, or unusual skill will permit different shapes or tolerances to be satisfactorily met.

#### REVIEW QUESTIONS

1. What are the main characteristics of the hot working processes as compared with cold working processes?
2. How do the Hooker extrusion process and impact extrusion differ from conventional extrusion? For what type of parts is each used?
3. Define forging, upsetting, edging, bending, drawing, and punching.
4. Why is it not desirable to provide a blank for drop forging of such size that no flash is produced? Explain the purpose of the flash gutter. Why is it sometimes necessary to trim the flash once or even twice during drop forging?
5. Why does forging impart greater strength to such parts as crankshafts and ring gears than could be obtained by casting or welding an alloy of the same composition?
6. For what type and quantity of production is hand forging generally applied? Power forging? Drop forging?
7. Name the three types of drop forging hammers.
8. In drop forging, why is a breakdown impression sometimes used in the dies?
9. Name four principles that are normally considered good practice in the design of drop forgings.
10. What type of forging is done on the forging machine? What three rules govern the proportions of parts for upsetting on the forging machine?
11. What are the general advantages of forging as a manufacturing process?

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## CHAPTER XV

### COLD WORKING PROCESSES

By E. W. ERNEST

**15.1. Introduction.** By definition, working metal anywhere below the recrystallization temperature is cold work, but in practice, most cold working processes are performed at room temperature. This means that the cost of handling is reduced, the need for soaking pits and furnaces eliminated, and speedier production facilitated. In addition to those various cold working processes which are similar to hot working processes, there are numerous other operations performed cold (e.g., roll-threading, knurling, burnishing, and dinking). In fact, the variety is so great and the shades of meaning so slight, that the more important cold working processes will be defined to avoid confusion.

#### 15.2. Definitions of Cold Working Processes.

**BENDING:** A plastic deformation (exceeding the elastic limit) of a sheet, strip, or bar such as is performed on a hand brake<sup>1</sup> in contrast to forming which is a process accomplishing one or more bends about linear axes by making the metal conform to a die shape. The inner radius of curvature is generally specified.

**BLANKING:** A press operation cutting the outside contour of a punching. Cutting inside contours (i.e., holes and slots) is called piercing.

**BOARING:** Consecutive shearing of a hole or contour by a series of stepped cutting edges similar to a saw. Generally considered a machining operation (see Chapter XVII) but used in slow-acting presses for accurate sizing of holes or contours such as gear teeth and keyways.

**BURNISHING:** A smoothing, polishing operation accomplished by compression and/or friction; e.g., shaved blanks polished and sized by being forced through an opening having sides tapered slightly inward.

**COINING:** The compressive cold sizing of a metal used to obtain a smooth finish, close tolerance, or fine detail at less cost than machining.

**COLD ROLLING:** A drawing operation between rolls (no torque applied to rolls) performed below the recrystallization temperature, achieving smaller size, closer tolerance, increased hardness, and higher tensile strength.

**CRIMPING:** Producing flutes or corrugations. Often used to gather metal as for stove pipe joints.

**CUTOFF:** An operation which shears a punching from a strip or bar.

**DINKING:** Contour cutting and/or piercing by pressing a sharp, thin steel edge through sheet material lying on a flat hard wood platen. Rubber, leather, fiber, paper, felt, etc., may be blanked this way.

<sup>1</sup> A device which clamps the material along one side of the bending line and lifts it along the other side, forcing it to bend along the edge of the clamp.

**DRAWING:** A stretching process. In tube, rod, or wire drawing the metal is pulled through a die. In cup, shell, or deep drawing the bottom is pressed into a die and the walls are pulled in, hence the name.

**EMBOSSING:** A shallow drawing operation rarely over three thicknesses of the metal deep. Raised letters are often embossed in thin metal strip.

**FLANGING:** Any process producing a flange. A flange may be drawn on a shell, in which case crumpling is prevented by a flange clamp. A tube may be flanged, in which case the end of the tube is stretched and thinned as it is flared out. Wide flanges must be drawn; they cannot be flared.

**FORMING:** See Bending. Forming is often combined with other stamping operations, e.g., piercing, notching, cutoff, etc.

**HEADING:** A metal gathering or upsetting operation so named because it was originally used only for production of screw and rivet heads. Today heading is used to produce a wide variety of different shapes but the term is generally applied only to cold upsetting.

**KNURLING:** A cold working process in which a series of sharp serrations on a hardened steel roller are pressed into the material being knurled. Used principally to roughen surfaces for thumb screws, handwheels, etc. Operation usually performed on lathes or screw machines.

**LANCING:** A special form of piercing in which the entire contour is not cut, the blanked material remaining as a tab.

**PIERCING:** See Blanking.

**PUNCHING:** A general term for all cutting operations performed on the punch press, including blanking, lancing, and piercing operations. See Stamping.

**RIVETING:** A hammering operation in which the end of a metal pin (i.e., a rod or rivet) is pressed over or spread out. May be either a hot or cold working process.

**ROLL-THREADING:** A method of threading a part by pressing and rolling between two serrated dies.

**SEAMING:** The bending and flattening of an interlocking fold, e.g., a stove pipe seam.

**SHAVING:** A refinishing operation which cuts a small amount of material from the edge of a punching to gain finish, accuracy, and/or a square edge.

**SHELL DRAWING:** See Drawing.

**SPINNING:** A technique of kneading sheet material about a rotating form into a desired circular shape.

**STAMPING:** A general term covering all punch press operations including the squeezing operations such as embossing, coining, swaging, forming, and shallow drawing as well as the cutting operations listed under Punching.

**SWAGING:** A hot or cold hammering process in which the material is not fully confined. For example, a rod or tube may be reduced in diameter or tapered by swaging, i.e., repetitive blows between proper dies. Swaging machines rapidly open and close die halves (or quarters) on the work as it is fed between them. The dies themselves rotate.

**SWEDGING:** Practically a cold die forging operation in which the metal is confined and made to flow plastically into the punch and/or die impressions. Used extensively in displacing metal around a hole to obtain sufficient thickness in thin stock for threading. Coining is also a swedging operation.

**TRIMMING:** Cutting away excess material left from previous operations.

**UPSETTING:** The gathering of metal in a rod or bar to achieve a larger cross-section. Performed either as a hot or cold working operation.

**WIRE DRAWING:** See Drawing.

**15.3. Punch and Die Terminology.** The term *die* is often applied to an entire press tool including both upper and lower members, while the names punch and die are used to designate parts or sections of a complete die (see Fig. 15.1). When the name die is applied to a part of a press tool it refers ordinarily to the member that has an opening or cavity for blanking, drawing, or forming.

A *punch* is that part of a press tool which enters into the opening or cavity formed in the die section. The punch usually is the upper member, being attached to the press slide or ram.

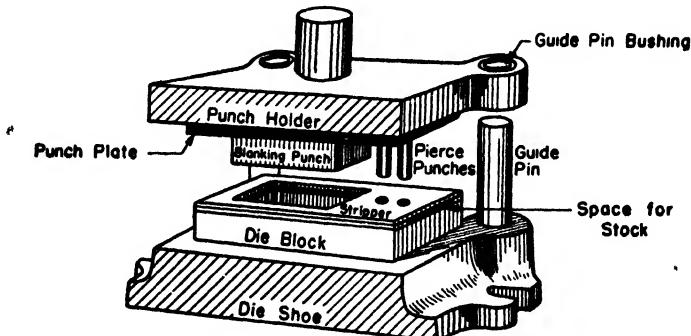


FIG. 15.1. Conventional die set.

A few notable exceptions to this conventional arrangement can be pointed out. Certain press tools are of inverted design and have the die affixed to the ram. Some kinds of dies have a blanking punch on the lower member in which there are holes to receive piercing punches from the upper member. Thus, one member may perform functions of both punch and die, and the location of a member cannot always be considered the criterion of function.

**15.4. Die Classification.** Press tools can be classified as single station cutting dies, noncutting dies, or progressive dies. The main types of press tools in use are listed under these divisions in Table 15.1.

*Single Station Cutting Dies.* The single station dies consist of a male and a female part operating on a stamping at one stroke of the press and at one positioning of the material. Such operations as blanking, broaching, cutting-off, dinking, piercing, shaving, and trimming are performed on suitable dies of this type. Other single station cutting dies include the following:

**COMPOUND BLANKING DIES.** A compound die usually has the die or female part on the top holder, and the punch in the lower holder. The inside of the die portion is fitted with a "knockout" plate operated by springs or by a mechanical knockout which operates at the top of the

TABLE 15.1. CLASSIFICATION OF PRESS TOOLS

<i>Single Station Cutting Dies</i>	<i>Noncutting Dies</i>	<i>Progressive Dies</i>
Plain piercing	Straightening	Plain pierce and blank
Plain blanking	Flattening	Pierce, blank, and form
Compound blanking	Upsetting	Blank and form
Compound pierce and blank.	Bending	Blank and draw
Compound blank and draw.	Forming	Trim, cutoff, and form
Shaving	Burnishing	Pierce, trim, cutoff, and form.
Trimming	Coining and swedging	
Trim and pierce	Extruding	
Cutting off	Hot forging	
Dinking	Cold forging	
Sub press	Expanding	
Horning	Hydrostatic	
Broaching	Assembling,	
Indexing	for press fitting assemblies, riveting, clamping over, seaming, staking, curling, wiring, and crimping.	
	Drawing	
	Redrawing	
	Reverse drawing	

press stroke to eject the blank after the ram of the press has ascended. The punch on the bottom holder is surrounded by a "stripper" which pushes the sheet back to the top surface of the punch after the die leaves it. Compound dies are used in blanking to maintain flatness and accuracy.

**COMPOUND PIERCE AND BLANK DIES.** A compound pierce and blank die carries both male and female parts on both moving and stationary parts of the die. The upper or moving portion carries the die part for cutting the outside contour of the stamping.

**COMPOUND BLANK AND DRAW DIES.** A die wherein the blank is first cut between the blank punch on one portion of the tool and a blank ring on the other. Then this blank punch functions as a clamp ring to prevent wrinkles in the part, which is drawn down into the draw die by the draw punch.

**TRIM AND PIERCE DIES.** Combine the functions of both named tools.

**SUB PRESS DIES.** A self-contained unit with four guide pins or other means for aligning punch and die. This tool is thus not dependent upon the alignment of the ram of the press for maintenance of clearance for its punch and die. The punch holder is not rigidly clamped to the ram of the press.

**HORNING DIES.** Dies built in the form of a horn or projecting part, for instance, for piercing a cylindrical object; the horn fitting inside the cylinder will carry the die.

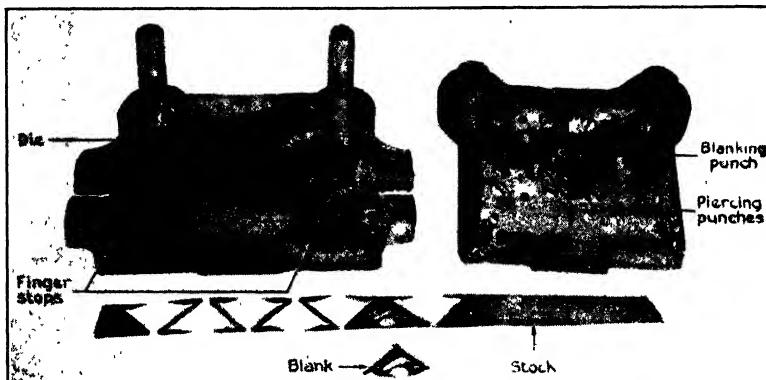


FIG. 15.2. Progressive pierce and blank die. Note how stock is run through dies a second time to utilize all of stock.

**INDEX DIES.** Used with index fixtures to produce a series of slots or holes in a circular punching by piercing one or more holes, then indexing to the next location.

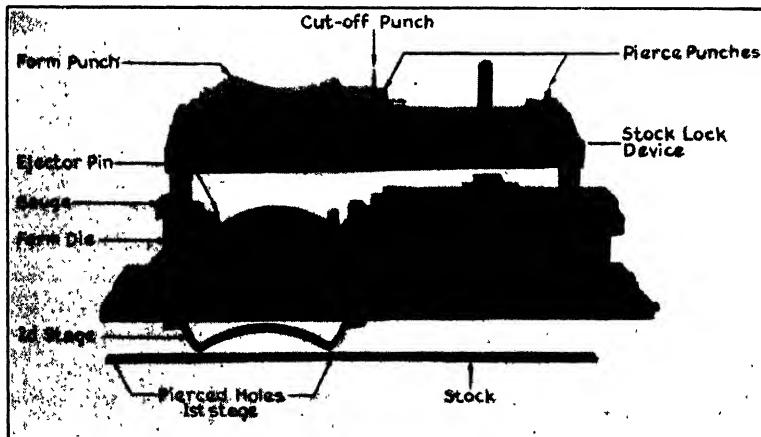


FIG. 15.3. Progressive pierce, cutoff, and form die for refrigerating-machine bracket.

**Noncutting Single Station Dies.** In one classification are dies suitable for bending, burnishing, coining, drawing, forming, swaging, and upsetting. Other dies in this class for other operations are as follows:

**STRAIGHTENING AND FLATTENING DIES.** Generally, two flat or stippled plates between which the blank is flattened with great pressure.

**EXTRUDING DIES.** Extruding dies are used to cold work materials by exerting sufficient pressure on the metal to cause it to flow between the punch and die. This process is used generally on the softer materials such as brass, aluminum, and copper.

**HOT FORGING AND COLD FORGING DIES.** For working metal hot or cold under drop hammers.

**EXPANDING DIES.** In which tubular parts are expanded by mechanical or other means.

**HYDROSTATIC DIES.** Operated by liquid pressure. Usually used for expanding purposes.

**ASSEMBLING DIES.** Used in assembling parts for press fitting, riveting, clamping, seaming, staking, curling, ironing, crimping, etc.

**REVERSE DRAWING DIES.** These dies are used to draw a shell inside out. This method is often used when the required reduction in shell diameter is at or near the practical limit for a single drawing operation.

**Progressive Dies.** Progressive dies may perform both cutting and noncutting functions in sequence at different stations of the die, each station or stop performing its single operation on the stamping for each stroke of the press. Under this classification are listed plain pierce and blank dies; pierce blank and form; compound pierce and blank; blank and form; blank and draw; trim, cutoff, and form; pierce, trim, cutoff, and form. All of the above are multiple operation dies, the functions of which are apparent from their names. They produce a complete blank from strip or sheet metal at each stroke of the press.

Figures 15.2 and 15.3 illustrate progressive die sets. The gage (in Fig. 15.2) and the finger stops (in Fig. 15.3) regulate the positioning of the stock before each stroke of the press.

**15.5. Types of Die Construction.** The dies used for producing punchings may be divided roughly into three types. They are conventional dies, continental dies, and stock dies.

The conventional type of die has a permanent die holder and punch holder. It is the most accurate, and is suitable for medium to high production depending on its construction. A die of this type is illustrated in Fig. 15.1. Each part is labeled.

Continental dies are of the push-through type illustrated in Fig. 15.4. The stock is first inserted between the guide and the die, and a loose punch is then placed in the guide on top of the stock. The ram of the press, striking the punch, pushes both punch and blank through the die.

Stock dies may be defined as dies of standard sizes, catalogued and

kept in stock for producing parts with little or no tool cost. They may be used in various combinations and make possible the production of stampings of almost any size or shape.

It is the designer's responsibility to design parts to make use of stock

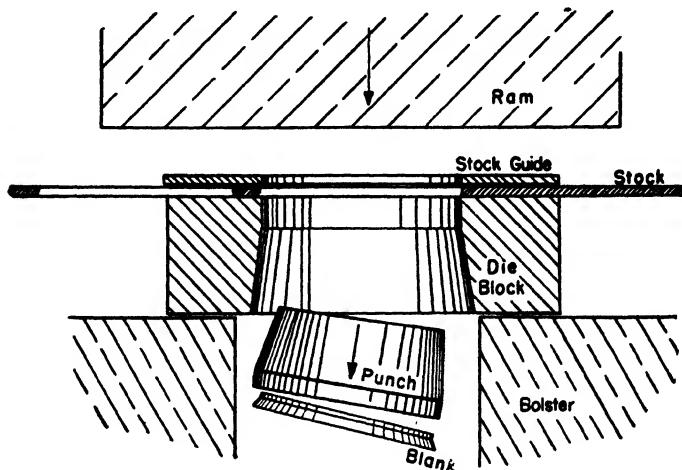


FIG. 15.4. Continental die set.

dies when the number of stampings is small enough that the extra labor costs of using them will not exceed the cost of special dies to produce the part. When a greater number of stampings is needed, or when the shape is not easily produced by stock dies, a special die is built. The

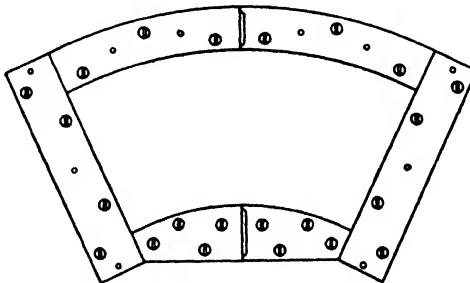


FIG. 15.5. Sectionally constructed die.

tool designer is usually given complete responsibility for choice and construction of such a die. He may choose to make it from a solid block, from separate pieces held as inserts in a cast matrix of a low melting point alloy, or from sections screwed to the die holders. The latter method is often desirable for dies to be used for large punchings

or for extremely high production, say a million or more pieces. The individual sections can be hardened separately, thus reducing warpage and loss in hardening. They also allow slight readjustment of the die opening to compensate for wear. A top view of a sectionally constructed die is illustrated in Fig. 15.5.

**15.6. Cutting Die Life.** Die life, as the term is used in press work, refers to the number of stampings a given die has produced, or is expected to produce, during its normal life. It is affected by many factors, most of which are associated with the design of the dies and their operation in the factory. The factors affecting die life that are directly related to the design of the part are (*a*) kind and thickness of the material, (*b*) quantity of parts per order, and (*c*) the shape of the part being punched.

As an example of the meaning of die life, consider a die made of water-hardening tool steel, punching 0.019 in. silicon steel such as is used for motor laminations. If such a die set is constructed with a straight punch and a one-half degree die clearance angle (Fig. 15.6),  $\frac{5}{16}$  in. may be ground off both punch and die during resharpening before the burr becomes too great or the punching becomes oversize. In continuous duty an average of 35,000 punchings can be expected per 0.012 in. grind, which means that the die can be ground 26 times before it becomes too large. Thus a total of 910,000 punchings is available from the die set, and this number of punchings is termed the *available die life*.

Recently a tapered punch has been developed which often extends the life of push-back die sets by permitting more than twice as much regrinding. The sides of these punches are made to taper outward from the punch face at the angle of the die clearance taper. Since equal grinds are made on punch and die during resharpening, the correct amount of clearance is maintained, and the set may be resharpened until the punching exceeds the allowable tolerance permitted on the drawing. Because the punch is tapered, it can enter the die only an amount permitted by the clearance; thus tapered punches can only be used on push-back die sets.

**15.7. Design of Blank Contours and Corners.** Blank shapes should be constructed with true radii, and, in general, rounded corners are preferable to square corners, as it is possible to work out a shape as at *B*, Fig. 15.7, more readily and cheaply than a square corner as at *A*.

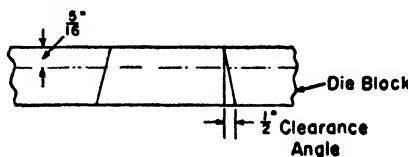


FIG. 15.6. Die clearance and thickness available for resharpening.

The rounded corner can be machined complete on a Keller die-sinking machine without subsequent filing or slotting. The Keller machine performs milling and profiling operations automatically with a template as a guide.

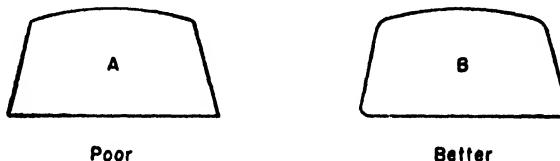


FIG. 15.7. Round corners for blank contours.

Some blanks which do not need to be cut around their entire periphery can be made from strip stock with a pierce and cutoff die, producing perfectly square corners, with no scrap material on sides or ends (Fig. 15.8). Sectional die construction also makes square corners preferable (Fig. 15.5).

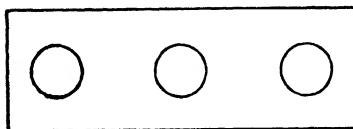


FIG. 15.8. Square corners for cutoff dies.

**15.8. Design of Projections.** The width of any projection or slot in a punching should be at least  $1\frac{1}{2}$  times the thickness of the material for  $\frac{1}{16}$  in. metal and heavier. For lighter gages than  $\frac{1}{16}$  in., these narrow

sections should not be less than  $\frac{3}{32}$  in. for economical tool manufacture and maintenance (see Fig. 15.9). Projections should be as short as

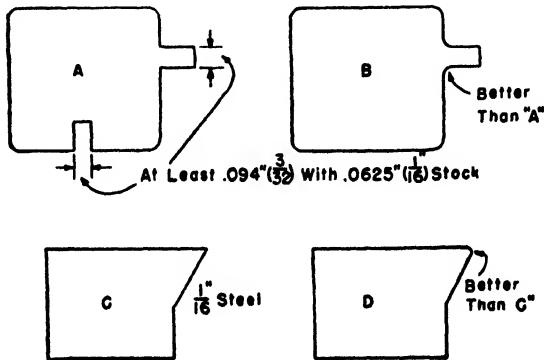


FIG. 15.9. Design of projections.

possible, since the longer and narrower they are, the more tendency there is for punch or die breakage in hardening and for excessive wear in use, with consequent high tool cost.

Points as shown in *C*, Fig. 15.9, should be avoided wherever possible, or made as blunt as design will permit, as these points make uniform hardening difficult and tend to increase die maintenance and decrease die life.

**15.9. Designs for Piercing.** When designing punched parts, care used in deciding the location, shape, size, and dimensions of pierced holes, slots, etc., will greatly reduce tool cost. The following are among the points that should be kept in mind:

Round holes should be used wherever possible in preference to slots or irregular shaped holes as the original tool cost and tool maintenance are less.

The diameter or least dimension of any hole should not be less than the material thickness and not less than 0.030 in. in any case. It is possible to punch holes of smaller dimensions than the material thickness, but this always means increased tool cost and maintenance, plus the consequent delay in production caused by tool repairs. Tool cost

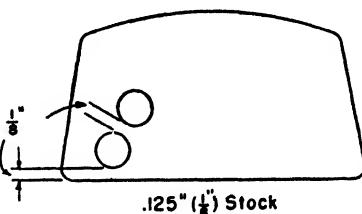


FIG. 15.10. Spacing between holes and edges.

is also increased by the necessity of providing inserts in the die (separate pieces dovetailed into the die block to prevent possibility of cracking in hardening), or special bushings containing groups of holes.

The distance from the edge of a hole to the edge of the nearest other hole or edge of the blank should be at least equal to the thickness of the material and greater wherever possible (see Fig. 15.10). Otherwise it is difficult to prevent distortion of the hole or edge of the blank.

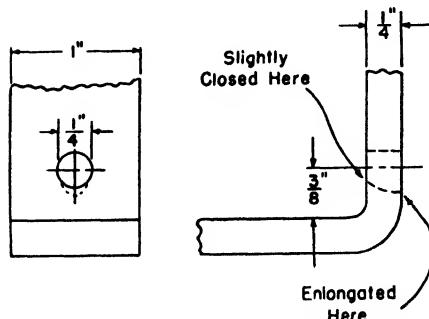


FIG. 15.11. Hole located near a bend.

Location of holes with respect to bends in the blank are important. Holes should be located as far as possible from bends. A condition as in Fig. 15.11, where the hole is located close to a bend, will cause distortion of the hole, as the bending action of the material elongates the hole if pierced before bending. To get a round hole, it is often necessary to add an extra operation to pierce the hole last.

Close tolerance between holes should be avoided, as this increases tool cost. It may often be possible to use larger holes to insure proper

location of a part in assembly, thereby increasing allowable tolerance of the center distances and diameters of holes.

The possibility of using stock dies for pierced holes should be kept in mind, especially when making comparatively small quantities of parts. Matrix alloy dies may make possible reduced die cost, particularly for punchings with a number of pierced holes.

**15.10. Tolerances for Punchings.** For economical tool cost, tolerances on blank dimensions should be as great as the design will permit. For

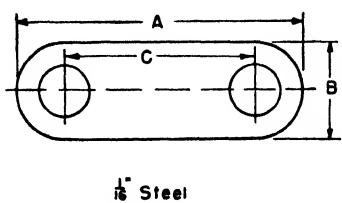


FIG. 15.12. A simple punching.

Condition	1	2	3
A	4 <sup>+0.010</sup>	4 <sup>+0.004</sup>	4 <sup>+0.002</sup>
B	1 <sup>+0.010</sup>	1 <sup>+0.004</sup>	1 <sup>+0.002</sup>
C	3 <sup>+0.010</sup>	3 <sup>+0.004</sup>	3 <sup>+0.002</sup>

instance, with the blank shown in Fig. 15.12, a tolerance of +0.010 in. on A, B, and C would mean that the tool could be used without fitting the punch and die by grinding. A tolerance of +0.004 in. on this punching means that the punch and die must be ground, adding approximately 35 per cent to the factory cost of the tools. If the tolerance is +0.002 in. or less, it would be necessary to add a shaving operation. This will mean an additional die, adding approximately 170 per cent to the factory cost for tools. The additional

operation will add 150 per cent to the original labor cost.

Sometimes smooth edges and close tolerances are necessary only on part of a blank. If so, this should be specified, since it is often possible to incorporate a shaving operation on a progressive die, thus eliminating a separate operation.

It is to be noted that blanking tolerances are all given on the plus side. This is done because the size of the blank die determines the size of the blank produced; and as the die is ground for resharpening, the die becomes larger, owing to clearance angle on the sides, causing the blank to increase in size. For the tolerance on pierced holes, a minus tolerance is given. The diameter of a pierced hole is determined by the diameter of the piercing punch, and since the punch wears with use, the hole will become smaller and the tolerance should be on the minus side. Of course the hole in the die for the pierce punch also becomes larger with wear, but this only increases clearance between the punch and die and results in an increased burr. It does not increase the dimension of the pierced hole in the blank.

Generally speaking, the kind and thickness of material used; the size of the part; the dimensions and number of holes or slots, and their

relation to bends, periphery, and other holes, all affect the tolerances which can be maintained in blanking, piercing, and forming.

**15.11. Material for Punchings.** The material of which a punching is made is an important factor in its cost.

For piercing and blanking operations, most grades of material will punch satisfactorily, except that scaly material tends to shorten die life and to increase die grinding costs when a large quantity of punchings is to be produced.

Where forming operations are involved, it is often desirable to use a strip material, since greater thickness variations are experienced in sheet material, and these variations will destroy the uniformity of the bending angle.

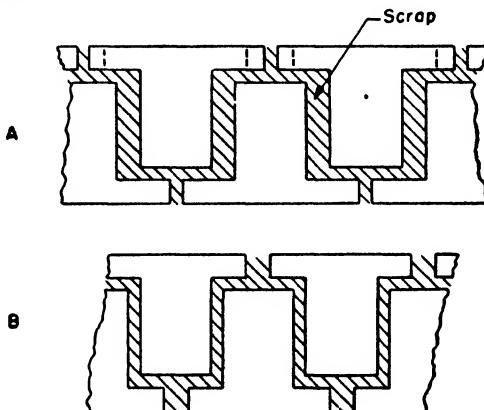


FIG. 15.13. Design for material saving. Note reduction in scrap in *B* obtained by shortening projecting ends to dotted lines in *A*.

Material for stampings involving swedged portions should be ductile. It is often necessary to "spot anneal" (anneal a small portion of the blank adjacent to the hole) to swedge to the required height without cracking. An annealing operation may also be needed on the corners of a drawn shell to avoid cracking during subsequent trim operations.

Where large quantities of parts are required, they are processed in automatic presses with roll feed. Here it is generally desirable to have strip stock in coils to reduce operating labor. This applies to all materials 0.044 in. thick and under. In some press shops, roll straighteners are available to straighten material before it is run through the feed rolls to the press. In this case, material even heavier than 0.044 in. is purchased in coils.

Steel is generally the cheapest kind of material. Stainless steel is hard to process and is comparatively expensive, but its use may reduce over-all cost by elimination of protective finish; brass, aluminum, and copper can be used to advantage for the same reason. The use of zinc should be considered instead of brass in many cases.

Material utilization should be studied carefully when designing punched parts. Often slight changes can be made in design of parts which will considerably lessen the quantity of material used. For example, consider the punching indicated in *A*, Fig. 15.13. In this punching

there is a considerable waste of material. If the projecting *T* ends are shortened as in *B*, Fig. 15.13, there is very little scrap material between blanks. Many other cases may be found where slight changes in blank shape or size will reduce the material used. It would obviously be of no help to widen the blank simply to utilize the material.

Whenever rings or circular pieces are required (Fig. 15.14) or any punching involving the piercing of a comparatively large center, the apparatus should be studied to see

FIG. 15.14. Utilization of scrap centers.

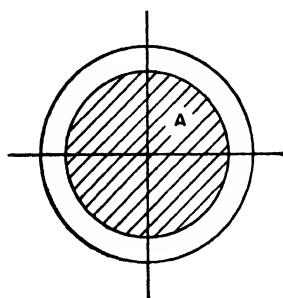
if some other part cannot be designed in such a manner that the scrap center (*A*) can be used in producing it.

If the quantity of parts required is fairly large, it is desirable to consider the use of ribbed construction to reduce material thickness and swedging of holes to obtain necessary thickness for threading.

**15.12. Punching Cost.** The type of die selected for a given punching should in general be the die that will produce it at the lowest total cost. In selecting a die the following factors should be considered:

- (a) Total quantity of punchings to be produced.
- (b) Rate of production required.
- (c) Direct labor cost per 1000 punchings.
- (d) Material punched.
- (e) Cost of dies.
- (f) Cost of maintaining dies.
- (g) Cost of setting up dies.
- (h) Time required to produce dies.
- (i) Expected life of dies.
- (j) Flatness and accuracy of punching.

As an example, assume that a customer requires 200,000 disks of  $\frac{3}{4}$  in. diameter. They are to be made of  $\frac{1}{16}$  in. common sheet steel.



Consider two methods of making these punchings: (1) using stock dies; (2) using a 5-gang die.

In order to effect material economy these disks must be punched as shown in Fig. 15.15.

In the first method a single punch and die is used, but the operator staggers-punches the material to obtain economy as shown in Fig. 15.15. This is done by locating material over the die by eye, and although there will be slightly more material used with this method than with a 5-gang die as in the second method, where the least possible spacing between blanks is built into the die, for the purpose of this comparison the material utilization is considered equal for both of the methods.

The following data may be used in selecting the type of die most economical for the above conditions. (No future use for the die is contemplated after the present order is completed.)

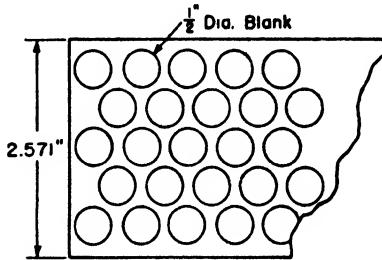


FIG. 15.15. Nesting of disks for material saving.

	<i>Stock Die Method 1</i>	<i>5-Gang Method 2</i>
<b>Costs</b>		
<b>Die cost:</b>		
Labor	..	\$40.
Material	..	\$2.
Total	..	\$42.
<b>Operating cost:</b>		
Labor per thousand punchings	\$0.335	\$0.0235
Total	\$67.00	\$4.70
<b>Cost of setting up tools</b>	\$0.29	\$0.64
Maintenance (including grinding and resetting), 3 grinds	\$0.60	..
<b>Total cost</b>	\$67.89	\$47.34

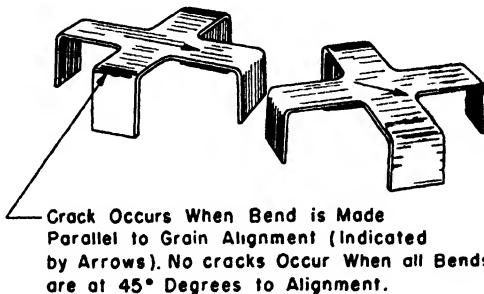
The low operation cost shown in method 2 is possible because this die can be run in an automatic press at a speed of approximately 150 strokes per min, producing 5 disks per stroke or 750 per min, whereas method 1 requires the use of a die in a hand operated press, producing one blank at a time.

From the above figures it is apparent that with the quantity indicated, a gang die should be made. Had the quantity been 100,000 or less, it would have been more economical to use the stock die method.

**15.13. Forming.** Form dies take a variety of shapes and are often used in combination with piercing, cutoff, and other operations. Where parts are pierced, formed, and cut off in the same die, it is often very

difficult to maintain a right angle at the bend, especially in the harder materials, owing to the spring-back of the material. Therefore, the designer should, where possible, allow for a slight deviation from an exact  $90^\circ$  angle. This is especially true with heavy material, for instance 0.094 in. thick. If exactly  $90^\circ$  is required, it may be necessary to build a more complicated die, thus adding to the tool cost, or an operation may be added, thus increasing the labor cost.

Wherever possible, forming should be done at right angles, or nearly so, to the grain of the stock (that is, to the length of the strip used).



**FIG. 15.16.** Mutually perpendicular bends should be made at  $45^\circ$  to grain alignment.

Bends made parallel, or nearly so, to the grain of the material often cause fractures on the bending line. Where bends must be made at right angles to each other in the same punching, it is often desirable to have them occur at  $45^\circ$  to the grain of the stock. (See Fig. 15.16.)

It is often desirable to have a hole in a piece being bent to prevent creeping of the material while the piece is being formed in the die (Fig. 15.17A). However, if the pierced hole cannot be tolerated, creeping can be prevented by adding "spurs" or sharp points in the form punch to engage the material being formed (Fig. 15.17B). This latter method will leave marks on only one side of the formed piece.

For ease of manufacture, the lengths of bent portions of a blank should have as large a tolerance as possible (Fig. 15.17A). The height of short tabs and other formed portions of a blank should be at least  $1\frac{1}{2}$  times the material thickness, as forming becomes exceedingly difficult below this dimension (Fig. 15.17C).

Sharp radii in the thick materials should be avoided. Radii no smaller than the material thickness should be specified, as a rule (Fig. 15.17D).

The use of spring materials where parts are to be formed (e.g., phosphor bronze, spring steel, etc.) makes it very difficult to get uniform

bending. This same thing is true in a lesser way of the harder grades of stamping steel and brass.

The designer can often help the tool room reduce the cost of the tool and shorten delivery of it by specifying the blank development of a formed part on the drawing. It is common practice for the designer to specify the approximate development, but when this is done, in order to determine the exact blank size necessary to form the part to the drawing, it is necessary for the tool room to first make the final form die, and, by a

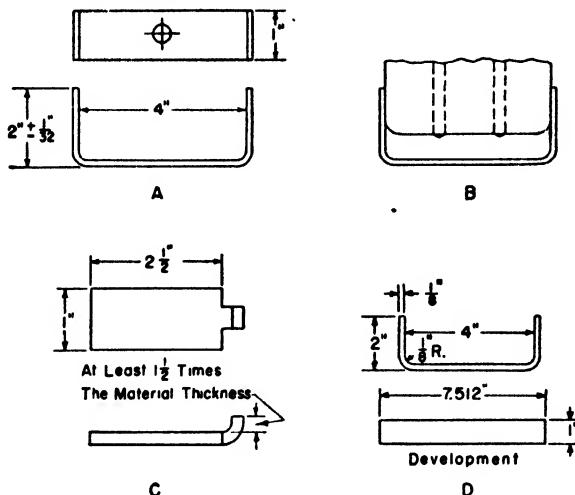


FIG. 15.17. Several designs for forming.

cut-and-try method, keep experimenting with various size hand-cut blanks on this die until the dimensions of the part after forming are in accordance with the drawing. However, if the dimensions of the formed part are not too important, it is often possible for the engineer to specify the exact development on the drawing, thus eliminating the necessity of development in the tool room. This will save time by allowing fabrication of both the blank and form dies simultaneously (Fig. 15.17D).

**15.14. Shell Drawing Design.** In designing shells for production on a punch press, the following general comments may assist in obtaining lowest tool and manufacturing cost consistent with design requirements.

**Round Shells.** Round shells always involve less tool cost and generally less manufacturing cost than shells of a rectangular or irregular shape. Drawing punches, dies, and other parts for producing round shells can be turned on a lathe and ground on a cylindrical or universal grinder much quicker than the machining of irregular shaped dies which must be worked out on the comparatively slower Keller machine,

shaper, etc. Also, hand grinding and stoning for punch and die clearance is eliminated. Manufacturing cost is often greater for rectangular shells, on account of the comparatively small radii in corners, which necessitate extra operations to draw successfully.

*Flanges on Shells.* Shells with flanges generally involve higher manufacturing cost and tool maintenance than shells without flanges. The latter are pushed straight through the die by the punch, whereas shells with flanges must be drawn in and pushed back out of the die. This slows up the drawing operation, and generally causes increased handling. To return the shell to the top of the die, a pad is necessary. This pad is actuated by springs or by a mechanical knockout, pushing shells out of the die on the return stroke of the draw punch. Shells with flanges, in being pushed back through the die, create considerably more die maintenance by causing almost twice the wear on the die. Also, to prevent score marks on the sides of shells, flanged-shell dies must be polished more frequently.

There are cases where a flange is to be desired, for instance, in rectangular or irregular drawn shapes (Fig. 15.18a). The trimming of this shell involves a trim die similar to a blank die, whereas if no flange were shown, as in Fig. 15.18b, it would be necessary to trim to height (involving considerable tool cost), or

draw with a flange, trim, then redraw to remove the flange, which increases manufacturing cost. Sometimes when no flange is desired, it is possible to draw a part with a flange, then trim very close to the side, producing an edge as shown in Fig. 15.18c. This condition should be shown on the drawing, if permissible. Also, if the sides of a drawn part are not too high (say  $\frac{1}{10}$  of the shell diameter), it may be possible to develop a blank which will

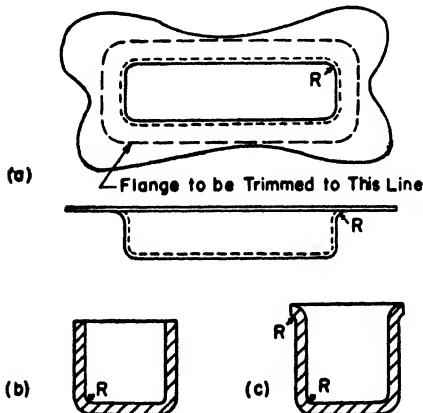


FIG. 15.18. Trimming of drawn shells.

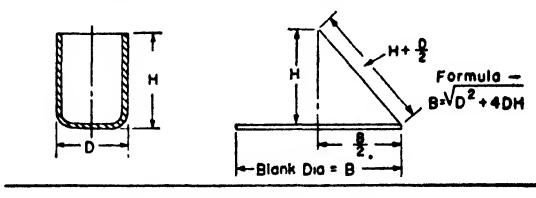
draw near enough to desired height to eliminate trim. In these cases, the tool department should be consulted to determine what variations in height may be expected.

*Height of Shells.* In drawing round shells, the maximum height that can be drawn in one operation is governed mainly by the diameter of the shell, the kind and thickness of material used, and the radius in the bottom of the shell and under the flange (if there is one). Too great a

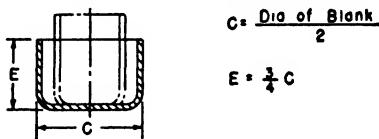
variation in material thickness will cause a variation in height of drawn shells and will sometimes cause excessive breakage. Thus, it is often advisable to use strip material for shell drawing since the greatest thickness variations are found in sheet stock.

In drawing steel, a reduction of 50 per cent from the blank diameter can generally be obtained if the material is of deep drawing quality. This figure is calculated as the difference between the blank and cup diameters divided by the blank diameter.

#### Graphical Method of Determining Blank Dia. of Cup

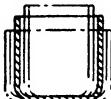


#### Dimensions of First Draw



#### Percentage Reduction of Diameter "C"

Based on Thickness and Material



Thickness	Alum & Steel	Brass
1/8	20 %	30 %
1/4	15 %	24 %
3/16	12 %	18 %
1/2	10 %	15 %
5/16	8 %	12 %

FIG. 15.19. Deep drawing design data.

To figure the approximate blank diameter of a given round shell without flange, the formula is

$$D = \sqrt{d^2 + 4dh}$$

where  $D$  is blank diameter,  $d$  is diameter of shell, and  $h$  is shell height.

In order to obtain the percentage reduction shown in Fig. 15.19, it is often necessary to anneal or copper plate when using certain materials. When drawing steel, stainless steel, brass, and copper, annealing is often used to overcome the work hardening caused by drawing operations. Copper plating is also being used extensively on steel shells before redrawing. The film of copper reduces die wear considerably and seems

to act as a lubricant to prevent score marks and facilitate the drawing action. Various other lubricants are also used.

Where shells are to be drawn at, or anywhere near, the maximum permissible reduction percentages, radii in the bottom and under the flange ( $R$ , Fig. 15.18) should be as large as possible.<sup>1</sup> It is rather difficult to confine this to a rule, but in medium thick material ( $\frac{1}{16}$  to  $\frac{1}{8}$  in.) the radius should be at least six times the thickness of material. For thinner materials this proportion should be increased and for heavier it may be reduced. Shells with too small radii generally require extra operations involving extra tool and manufacturing cost. Radii in corners of rectangular shells (Fig. 15.18) should be as large as possible for the same reason.

**15.15. Recommended Shell Tolerances.** Table 15.2 lists recommended tolerances for round shells of various materials. With rectangular or irregular shells, tolerances should be approximately 20 per cent greater than in Table 15.2.

All of the drawing tolerances listed are based on the first draw from a shell, the height of whose sides is from  $\frac{1}{2}$  to  $\frac{3}{4}$  the diameter of the shell. If the sides are lower, it is possible to hold the shell to closer limits. Of course, closer limits can also be maintained by "redrawing" or "sizing." This, however, usually entails increased tool and labor cost.

TABLE 15.2. RECOMMENDED SHELL TOLERANCES

Round shells — steel, brass, copper, aluminum, zinc

<i>Thickness of Material</i>	<i>Up to 2 in. diam.</i>	<i>Up to 6 in. diam.</i>
Up to $\frac{1}{32}$ in.	$\pm 0.005$ in. (inside diam.)	$\pm 0.008$ in. (inside diam.)
$\frac{1}{16}$	$\pm 0.006$	$\pm 0.010$
$\frac{3}{32}$	$\pm 0.008$	$\pm 0.012$
$\frac{1}{8}$	$\pm 0.010$	$\pm 0.015$
$\frac{1}{4}$	$\pm 0.015$	$\pm 0.020$

**15.16. Metal Spinning.** Metal spinning is a technique for forming round sheet metal parts at low cost. Complex cylindrical shapes can be spun in aluminum, copper, pewter, zinc, brass, low carbon steel, and certain of the alloy steels, including stainless steel.

The machine used for making spun parts is a lathe which is larger, more powerful, and normally has a greater swing than the familiar wood-turning lathe. A form which has the same shape as the spinning to be produced is first turned on the lathe from either wood or metal. For large work, wood is usually preferred because it costs much less. This form serves the same purpose in spinning that a die serves in forming. It is much lower in cost than the corresponding die, but can be

used over and over again for making duplicate parts. The form may also be made so that it can be dismantled for removal from the finished spinning. Partially closed ends and reduced sections may thus be spun that would be practically impossible to draw.

The form is usually fastened directly or through a backing plate to the head plate of the spinning lathe, and the round sheet metal blank which is to be spun is pressed against the form by the tailstock. When the lathe is started, both the blank and form are rotated at high speed. The operator, beginning at the center, works the metal against the form with blunt-ended hard wood or steel rods. A skilled operator can fit the metal to a small and simple form in just a few minutes. Intricate articles may require several operations with intermediate annealing before they are spun to the finished shape.

The skill of the operator plays a very important part in successful spinning, not only in limiting work hardening, but in using the proper tools with the proper pressures to form the desired shapes. The tools and technique of spinning are considered "stock in trade" and are very closely guarded.

Spinning is not a new process. In fact, it has been used for years to make trophies, loving cups, cooking utensils, chandeliers, lamps, reflectors, urns, and other similar articles. In industry this method of forming parts has been found particularly applicable for small orders of, say, up to 20 duplicate pieces. It is used for model work in conjunction with development and research, and for parts for the specially engineered industrial or apparatus lines. The small parts may be held to good accuracies, and all the parts have characteristic good strength, which is introduced by cold working, light weight, and smooth surfaces.

As with most other special processes, the designer can often save time and improve his product if he will consult the experienced operator in the early stages of design. Simple changes in shape may often eliminate an annealing operation, or make the wood form much simpler, and attendant savings result. Usually it will be found that the various forming and shell drawing operations are less expensive than spinning if the quantity desired is large.

As an example of some of the industrial uses of this process, the following list of spun parts is included. Future applications are not of course limited to work which has already been done, and any article having circular symmetry is a prospect for this method of manufacture.

Bell mouth nozzles.

Containers and receptacles.

Air deflectors for large generators.

Cylindrical, conical, parabolic, and shaped pipe, rings, covers, and dishes.

Mandrels for making paper cups.

Engine cowls for airplanes.

Injector sleeves for Diesel engines.

Table service.

**15.17. Cold Heading Process.** Cold heading is a cold upsetting process used to produce a great variety of small machine parts from wire stock. It is so named because it was originally used only for the production of heads on rivets and screws. Today its field of application is considerably wider.

In principle and operation, a cold heading machine is much like a forging machine except that it takes wire in reel form, cuts off the required lengths, and carries them through the upsetting operations automatically. Once set up, a heading machine can turn out 150 to 300 pieces a minute with no more attention than a periodic inspection. This feature accounts for the remarkably low cost of cold headed products.

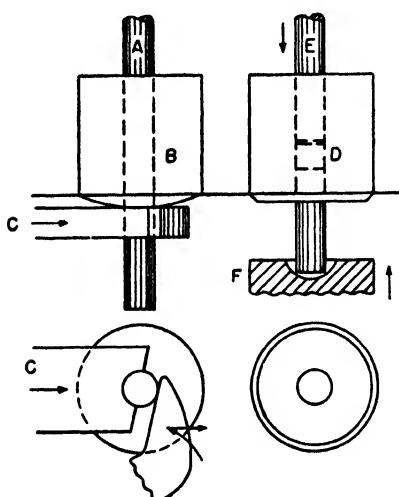


FIG. 15.20. Cold heading.

The principal limitation of this process is the size of the parts that can be made, since the power requirements for a given size are much greater than for hot upsetting. Wire up to  $\frac{5}{8}$  in. diameter is commonly handled by this process. The severity of upset possible without splitting the metal or buckling it is also somewhat less than in hot forging.

**15.18. Cold Heading Tools and Their Action.** Fig. 15.20 shows the setup for producing a simple rivet. The straightened wire stock, *A*, is fed through the cutoff die, *B*, until the proper amount protrudes. The

shear, *C*, then moves in, severing the protruding portion and carrying it over to the upsetting die, *D*. The punch, *F*, moving forward, shoves the blank into the die, *D*, until it strikes the stop pin, *E*. The continued travel of the punch upsets the protruding end of the blank, forcing the metal to assume the shape of the punch cavity. As the punch recedes, the stop pin, *E*, moves to eject the finished rivet from the die.

When a length no more than  $2\frac{1}{2}$  wire diameters must be upset, a single operation is usually sufficient. When more material than this is required (up to a maximum of about five diameters), a double-stroke operation must be employed. In this case, two punches act in succession on the blank while it is in the upsetting die, the first or coning punch (Fig. 15.21b) gathers the stock into a stable nonbuckling cone, the second or finishing punch (Fig. 15.21c) produces the desired shape.

In either single- or double-stroke heading, a part of the shape may be machined into the die as well as the punch. Indeed, for flat-headed screws, the entire finishing impression is in the die.

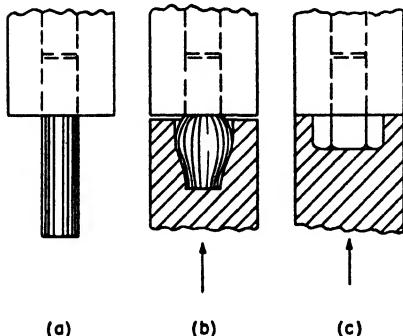


FIG. 15.21. Double stroke heading. (a) Original stock in position for heading, (b) first stroke heading, to an intermediate form, and (c) second stroke heading to final form.

For parts where over nine diameters of the stock are in the die, the upsetting of the portion within the die makes it stick so tightly that the ejector pin may not be able to remove it. Therefore, an open die is

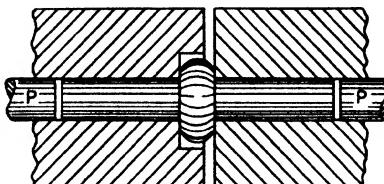


FIG. 15.22. Upset not on the end.

used. The stock is made to come in through grip dies as in the forging machine. After heading, as with a solid die, the dies separate, and the part, severed in the meantime from the stock, drops out.

By making a hole equal to the wire diameter and of the proper depth in the punch, an upset may be produced in the middle of a piece as shown in Fig. 15.22. Ejector pins, *P*, must be provided in both the punch and the die. Double-stroke upsets are possible with this class of work but are difficult because there must be two ejections from the punch.

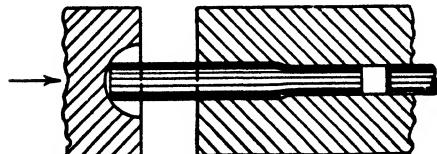


FIG. 15.23. Extrusion of thread section.

When a screw is to be roll threaded (see Sec. 15.20), it is often desirable to reduce the diameter of the threaded portion so that the threads will not extend above the body of the screw in the finished product. To produce this reduction, the thread end of the die is made to the required

smaller diameter and the stock is forced into it by the punch (Fig. 15.23). When the extruded portion strikes the ejector pin,  $P$ , the upsetting of the head proceeds in the usual manner.

**15.19. Materials for Cold Heading.** Any metal that is reasonably malleable and does not work harden excessively can be cold forged in a header. This includes low carbon steels, low alloy steels, structural stainless steel, and almost all nonferrous alloys.

**15.20. Roll Threading.** Roll threading is a method of producing external threads by rolling the part to be threaded between two hard

serrated plane dies that form the threads by a squeezing action. This process frequently follows cold heading as a means of making a complete screw without machining.

Figure 15.24 shows diagrammatically a pair of roll threading dies with a screw blank between them. On the faces of the dies are long, straight projections having the profile and pitch of the desired thread and inclined to the line of travel by an angle equal to the helix angle of the screw. The two dies are set so that the distance between the roots of the die teeth equals the outside diameter of the finished screw. Then, if the blank is prepared with a diameter approximately equal to the pitch diameter of the screw, metal will be displaced from the region below the pitch circle of the screw to form the peaks of the threads beyond the pitch circle when the blank is rolled between the dies as indicated in Fig. 15.24.

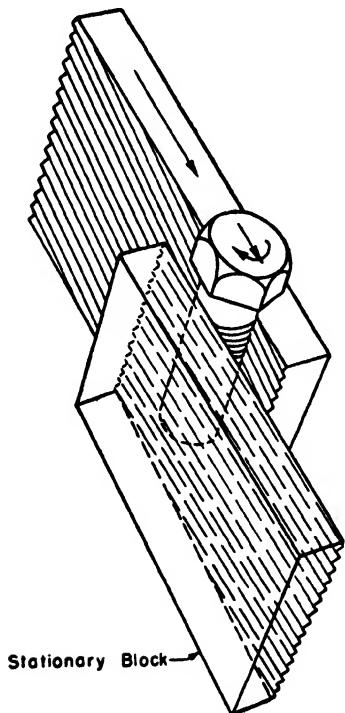


FIG. 15.24. Action of roll threading dies.

As in cold heading, the screw blanks are fed automatically. This makes high production at low cost possible.

While not as accurate as the best cut screws, roll-threaded screws meet most commercial requirements (class 3 fit), and they are as much as 20 per cent stronger than cut threads.

**15.21. Conclusion.** When designing apparatus with a limited expected production there may be times when it is advisable to use ma-

ching, spinning, casting, etc. This is especially true where design requirements are rather inflexible and complicated and where stock tools are not available. The cost of punching or heading tools may overbalance the saving on manufacturing cost. But wherever the anticipated production quantities are at all sizable (often as low as two or three hundred pieces), the apparatus should be closely analyzed to determine the advisability of modifying the design for press or header processing.

As the anticipated production increases, so does the need for simplification of design. With a production of only a few hundred pieces, the total manufacturing cost of all parts to be produced may not be great enough to be materially affected by the elimination of an operation. However, where hundreds of thousands of parts are involved, a slight change on a part to permit a reduction in the size, kind, or thickness of material, or the elimination of even one operation, will often result in prodigious savings.

It is often possible to avoid the use of expensive tools by making a punching in two or more pieces, which may be welded together by arc, atomic, line or tack welding, or spot welding. Many times it will be found that the component parts may be processed on existing stock dies, thus eliminating tool expense.

Often the equipment available dictates the trend in design, and it will be found that many times a discussion of the part in question, between the designer or engineer and the factory personnel, will bring about recommendations of changes which, while retaining the limiting elements of design requirements, will greatly simplify manufacturing procedure.

#### REVIEW QUESTIONS

1. Press tools for cold working operations contain a punch and a die. Which parts are usually designated by these terms?
2. What is meant by a single-station die? How does it differ from progressive dies?
3. Dies used for producing punchings may be divided roughly into three types. Name and describe each of them.
4. Describe what is meant by available die life. Name three factors related to the design of a part which affect die life.
5. When a sectionally constructed die is to be used, what type corners are preferred? When cutting off strip stock? When blanking?
6. What general rule is normally used as a limit to the minimum size of hole that should be pierced? How close may holes be placed to an edge in normal practice? To a bend?
7. Should the tolerance on blanked parts be given on the plus side, the minus side, or split both ways? How should the tolerance on a pierced hole be specified?

8. Name at least five of the factors which affect punching cost and should be considered by the tool designer when selecting a die.
9. Explain the metal spinning process. What shapes can be produced? Under what circumstances is this process used advantageously?
10. For what type of work is cold heading employed? Explain the roll threading process. What preparation must a headed bolt receive if the outer diameter of a rolled thread must not be greater than the unthreaded stock diameter?

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New York, 1941.

## CHAPTER XVI

### WELDING AND ALLIED PROCESSES

**16.1. Introduction.** Welding is defined as the intimate joining or consolidating of metals through the application of heat, or through the application of heat and pressure combined. The many methods by which welds may be made are therefore classed as pressure and non-

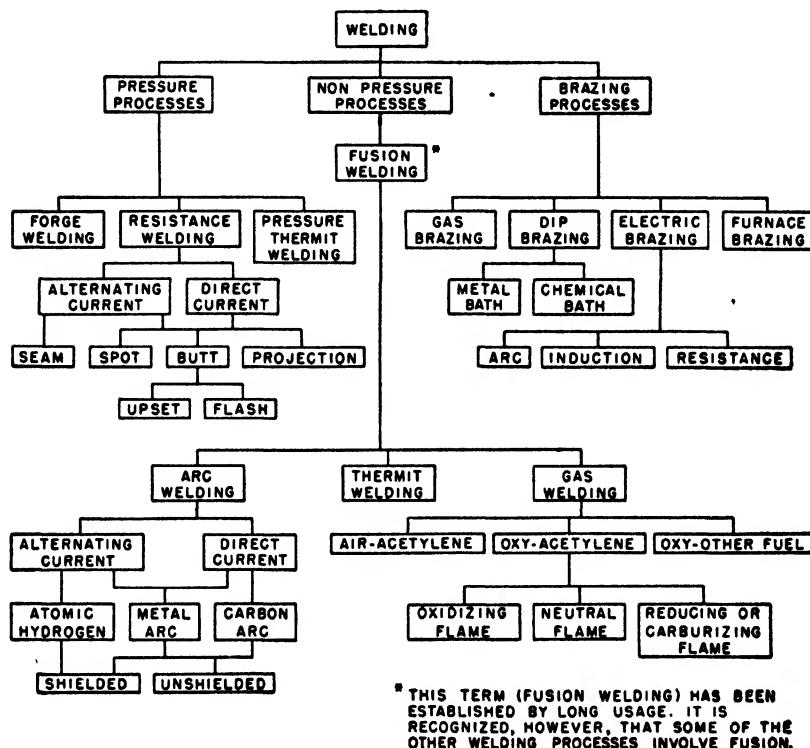


FIG. 16.1. The American Welding Society's master chart of welding processes.

pressure processes. In some, the parts are fused (melted) together. In others, they are forged together when in the plastic state. It is customary also to distinguish a third class of welding known as the brazing processes. These processes differ from the others in that a dissimilar

lower melting point filler metal is used to join the parts, and the parts themselves do not melt, and no forging action is present.

The methods of heating commonly employed with each of these three welding processes are indicated on the master chart, Fig. 16.1. In the electrical industry, the brazing processes, resistance welding, and arc and gas welding are of most importance. Each of them will be discussed in this chapter, along with several other processes closely associated with the purpose of welding or the equipment used for welding. The allied processes to be discussed are soldering, which is related to brazing in purpose, and metal cutting and metal spraying, which make use of gas torches and other equipment similar to that used for nonpressure welding.

## BRAZING

By R. S. PELTON

**16.2. Definition of Brazing.** Brazing is defined as a group of welding processes wherein metallic parts are joined by a nonferrous filler metal or alloy whose melting point is higher than 1000 F (540 C) but lower than that of the metals or alloys to be joined. In other words, brazing is understood to mean the joining of iron, steel, copper, nickel, and their alloys, and other metals in either similar or dissimilar metal combinations by means of a nonferrous filler material melting at approximately red heat or above.

Particular brazing processes may be restricted in their use by inherent limitations; nevertheless, so much can be accomplished by all of these methods that applications are found in practically all industries. In the electrical industry, brazing has become of importance primarily through the development of low melting point alloys and convenient methods of heating.

**16.3. The Brazed Joint.** To form a truly brazed joint, the molten filler metal must wet the surfaces of the parts being joined, and must be held in the joint so as to fill the free space. In addition, a limited amount of alloying between the filler metal and base metals usually takes place at the elevated temperature. As a result, when a brazed joint is properly made, its strength is somewhere between that of the cast filler metal alone and that of the base metal. The factors upon which the strength depends are:

- (a) *The nature and strength of the base metals.*
- (b) *The nature and strength of the brazing alloy.* The various brazing processes are frequently classified according to the filler used. There are four common types of fillers: copper, spelter and bronze, silver alloys,

and aluminum alloys. They will be discussed in that order in the following sections.

(c) *The clearance of the parts being joined.* Except for brazing with copper in a controlled atmosphere, the filler will not enter a joint between two pieces if they are held too tightly together. On the other hand, if the opening is too great, the resultant strength will be that of pure cast filler alloy. There seems to be an optimum spacing for each filler.

(d) *The cleanliness of the materials involved.* If either maximum or uniform strength is wanted, too much attention cannot be given to having the surfaces to be joined, the fillers, and the fluxes all clean and fresh.

(e) *The use of a flux.* A flux is intended to protect the cleanliness of the surfaces and to promote the flow of filler into the joint.

(f) *The heating and cooling of the assembly.* The important thing about cooling is that the joint should not be disturbed in any way while the filler metal is cooling through its plastic range, and no load should be placed on the joint until it is cooled appreciably below the softening point of the alloy. If pressure is applied to hold the parts together while heating, the pressure should not be released until the filler metal is solid. Sometimes the brazing processes are classified according to the method of heating. The common methods will be discussed in a later section.

**16.4. Copper Brazing.** The high melting point of copper (1982 F) limits its applications as a brazing material to ferrous metals and other similarly high melting point alloys, including high-speed steel and tungsten carbide. Copper is most frequently used in furnace brazing with a protective atmosphere, since under these conditions it is extremely liquid and often wets and flows over the surfaces very rapidly. It is practically impossible to get a joint too tight or too well fitted for copper to penetrate it when a protective atmosphere is used.

Joints in steel parts brazed with copper have high strength resulting from a combination of copper penetration along the grain boundaries of the sides of the steel joint and the growing together of the grains so that the two surfaces are practically knitted together. This is illustrated by the photomicrograph, Fig. 16.2. The strength of copper-iron alloys which may be formed in the joint is indicated in Fig. 16.3. External fillets of copper usually are small and of little value compared with the alloy formed in a well fitted joint, especially if the layer of filler is thin.

*Applications.* Copper brazing is largely applied to assemblies made of low carbon steel in the form of stampings, screw machine parts, and tubing which can be heated in a furnace. However, alloy steel, such as nickel, nickel-chromium, molybdenum-chrome-vanadium, etc., can be copper brazed and afterwards heat treated to develop high strength



FIG. 16.2. Photomicrograph of a joint between two pieces of steel of slightly different analysis copper-brazed in an electric furnace with a controlled atmosphere. Approx.  $\times 100$ .

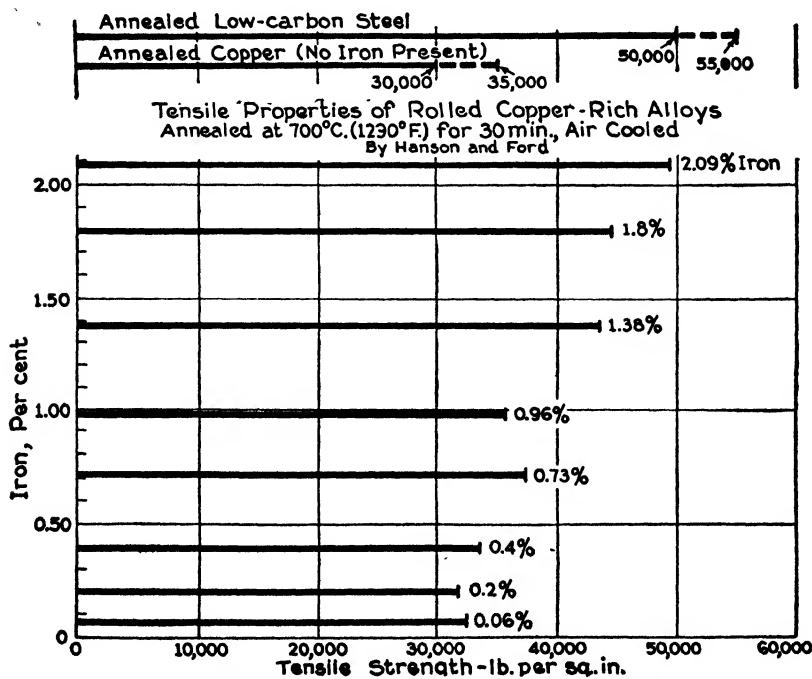


FIG. 16.3. Tensile strength of copper-rich alloys of copper and iron.

and hardness. The high chromium steels (stainless variety) do not lend themselves readily to copper brazing because the chrome oxides are not reduced by ordinary furnace atmospheres at brazing temperatures. The

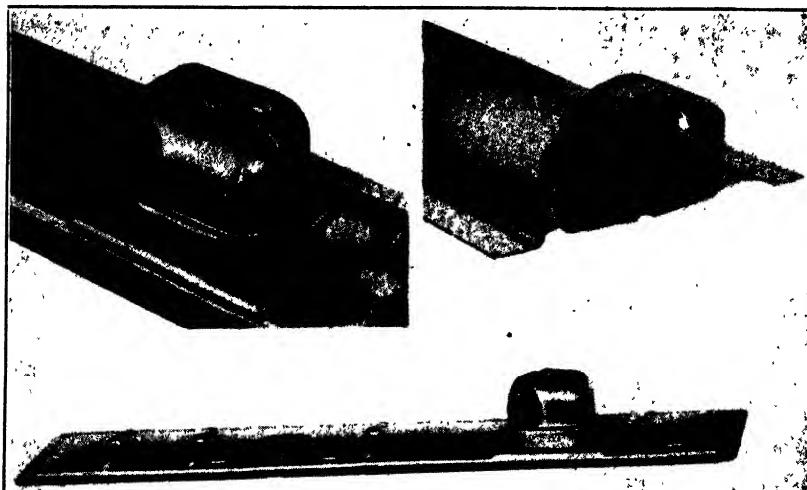


FIG. 16.4. Three views of a copper-brazed push rod cover for an automobile engine.

high affinity of copper for nickel results in poor penetration of copper into nickel or nickel alloy lap joints. To overcome this, it is best to plate or coat thelapping surfaces with copper a few thousandths of an

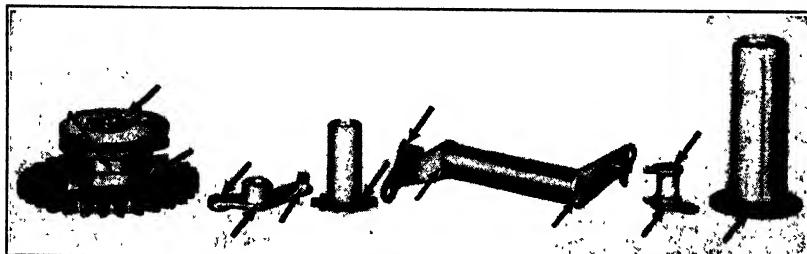


FIG. 16.5. Copper-brazed steel subassemblies for a cash register. Arrows indicate brazed joints.

inch thick, and to allow more clearance in the joint so the fluidity of the filler may be retained until the joint is filled.

Several examples of assemblies fabricated by furnace brazing with copper are illustrated in Fig. 16.4 to Fig. 16.8.

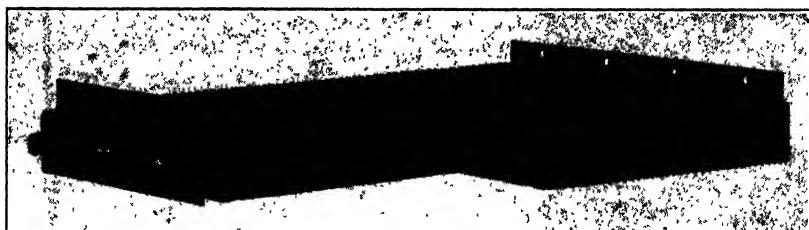


FIG. 16.6. Copper-braced steel fin condenser. Made entirely of stampings without tubing except for tubular end connections, as illustrated by cut-away section.

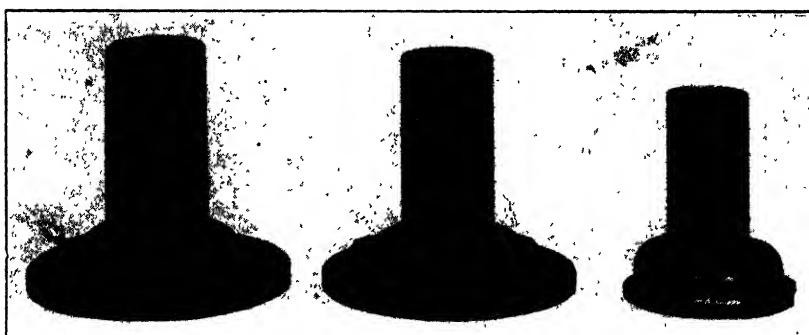


FIG. 16.7. Three designs of an automobile clutch-gear bearing retainer. Malleable iron casting weighing 2.5 lb (left); malleable iron casting machined weighing 1.5 lb (center); and new copper-braced construction from steel tubing and a stamping weighing 0.5 lb (right).



FIG. 16.8. Core (with part cut away) for automobile hot-air heater made of steel stampings and tubing, and copper-braced.

**16.5. Spelter and Bronze.** Common brass, called spelter, was probably the first material used to make a brazed joint in ferrous material. Brass could also be used for copper and some copper alloy parts, but it is seldom used any more, largely because of the objectionable distillation of the zinc during the heating period (zinc boils at 906 C). It has been replaced by nonfuming bronzes which cost less than silver alloys, and are especially suitable when large quantities of filler metal are needed and the high brazing temperature is not objectionable.

Tobin bronze, some silicon bronzes, and manganese bronzes work well, and are usually applied by hand with a torch. One type of application for them is on production where their strength at high temperature is desired. Their most common use is in salvage operations, particularly on castings. Table 16.1 gives the melting points of several common brazing alloys. Tobin bronze with a strength of approximately 50,000 lb per sq in. in tension is used on steel, cast iron, copper, and some alloys. The different brass manufacturers and brazing alloy vendors have different compositions which they recommend for certain applications. Nickel is an aid in brazing tungsten carbide, and several alloys on the market containing various proportions of nickel are recommended for this purpose. The bronzes are also used as a surfacing material when a better bearing surface is wanted on another material such as steel. A good brazing or welding operator can apply a thick layer of the bronze so that it can be machined to a good bearing surface.

**16.6. Silver Brazing.** Pure silver is seldom used in industry as a brazing metal because alloys of silver, for example, silver and brass, have a lower melting temperature and better melting and flowing characteristics. The brazing alloy having the lowest melting point known contains 50 per cent silver, and copper, zinc, and cadmium. This alloy is very fluid and less viscous than many other brazing alloys. Since zinc fumes, which may frequently be given off by these alloys, are objectionable in furnaces, zinc-free alloys, for example, silver and copper, are often used in furnace work.

A silver-phosphorus-copper alloy, known as Sil-Fos, is very useful for brazing copper and copper alloys. The phosphorus content makes this alloy self-fluxing on clean copper, but flux is needed on the copper alloys. This alloy should never be used on iron or steel since the phosphorus and the iron form iron-phosphorus alloys which are very brittle and may lower the strength of the surface layer of the steel to 40 per cent of its usual strength. Sil-Fos is not as free flowing as the other silver alloys, and therefore does not flow into tight fits as well, but for

TABLE 16.1. BRAZING FILLER METALS

No.	Trade Name	Composition in %			Temperature °F Soften	Temperature °F Flow	Specific Gravity as Cast	Elec. Conduc- tivity	Remarks
		Ag	Cu	Zn					
1	Copper	100				1982		100	Used mainly in furnace brazing.
2	Everdur 1010		95.8		3.1 Si 1.1 Mn	1867		6.7	
3	Brass	70	30			1750		26	
4	Brass	60	40			1650		25	
5	Tobinbronze	59	40.5		0.5 Sn	1625		20	Low cost, malleable.
6		10	52	38		1510	1600	5	
7		50	50			1435	1570		
8	Eutectic	72	28			1435	1435	9.95	77.1
9	ETX	50	34	16		1275	1425	9.37	24.4
10	NT	30	38	32		1370	1410	8.86	Satisfactory on brass. (Refer to text.)
11	Phos-copper	92	25	15	8 P	1305	1385		3.6
12	RT	60	80			1260	1325	9.52	Lower temperature, low zinc.
13	Sil-Fos	15			5 P	1185	1300	8.45	Self fluxing on clean copper. Do not use on ferrous or high nickel alloys.
14	Easy-Flo 3	50	15.5	15.5	16 Cd 3 Ni	1195	1270		For carbide tool tips.
15	Easy-Flo	50	15.5	16.5	18 Cd	1160	1175	9.49	Very fluid at brazing temperature.

most parts this difficulty can be avoided by preplacing pieces of the alloy in joints between flat surfaces.

A similar alloy without silver but with more phosphorus is marketed as Phos-copper. This alloy is likewise self-fluxing on clean copper, can be used on copper alloys with flux, and must not be used on ferrous alloys. Phos-copper is less expensive, particularly in the heavier gages. It is very satisfactory for joints where the members are heavy and rigid, but the phosphorus may diffuse into thin or flexible members and cause brittleness which is usually objectionable.

It should be noted that some alloys are more fluid or less viscous than others. This means that with proper technique and the proper alloy, fillets can be practically eliminated around a joint, or liberal-sized fillets may be obtained. If the proper alloy and technique are used, dressing or smoothing of the joint surfaces should seldom be necessary. When there may be danger of galvanic corrosion, the tendency may be minimized by eliminating fillets so that only the thin edge of the alloy is exposed.

For brazing copper, brass, and bronze with alloys high in silver, extra clearance should be allowed in the joint because the free alloying between these base metals and the silver will cause the latter to change in composition before the joint is completed. This change may reduce the fluidity and the melting point of the filler alloy to such an extent that that it is difficult to fill the joint.

The 18-8 type stainless steel can be silver brazed, but it should be remembered that the brazing temperature is in the carbide precipitation temperature range for this material, and if corrosion resistance is wanted, a stabilized grade of 18-8 stainless steel should be specified.

High nickel alloys, such as the Nichrome resistance wires, have a peculiar characteristic. In the fully annealed condition they braze very satisfactorily. But, when under strain, silver should be kept away from them because the molten silver alloy will penetrate rapidly along the grain boundaries and sever the wire.

**16.7. Aluminum Brazeing.** Aluminum brazeing alloys are used only for the brazeing of aluminum. As with any other metal, the brazeing of aluminum requires an alloy with a melting point lower than that of the parent metal and a flux which will dissolve the oxides at brazeing temperature. Furnace and torch heating were the first procedures which were developed and applied to production, but it is reported that the chemical bath method has shown considerable promise. For furnace brazeing, the best filler metal and flux depend on the parent metal as shown in Table 16.2. At this writing, no satisfactory brazeing technique

has been worked out for the heat-treatable aluminum alloys (11S, 14S, 17S, 24S, or 27S).

TABLE 16.2. FURNACE BRAZING OF ALUMINUM<sup>1</sup>

<i>Composition of Parts</i>	<i>Composition of Filler Material</i>	<i>Brasing Flux to be Used</i>	<i>Temperature Range °F</i>
2S and 3S	{No. 43 wire X-711 sheet}	No. 30	1160-1185
61S	X-716 wire	No. 33	1060-1090
No. 1 brazing sheet	Integral	No. 30	1160-1185
No. 2 brazing sheet	Integral	No. 30	1160-1185
No. 43 castings	X-719 wire	No. 33	1025-1050
No. 406 castings	X-716 wire	No. 30	1160-1185

#### TORCH BRAZING

All applications	X-716 wire	No. 33	...
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<sup>1</sup> Prepared from information supplied by the Aluminum Company of America. All designations are according to the system of that company.

The filler metal is usually applied in the form of wire or sheet metal washer as is common practice with other metals. A novelty, however, is offered here in that 3S sheet is available with a coating of the brazing material on either one or both surfaces. This is called, respectively, either No. 1 or No. 2 Brazing Sheet, depending on whether only one or both surfaces are coated. These coats are more than simple "pretinning," as there is enough brazing alloy to form fillets. Parts formed from this brazing sheet are brazed by merely coating the area at the joints with flux and heating to the proper temperature in a furnace.

The temperature required for brazing aluminum is above the recrystallization temperature so that any of the cold worked alloys are annealed by the operation. Design strength figures should be based on the annealed strength of the alloy. Sometimes, however, the 61S alloy can be quenched upon removal from the brazing furnace, and the parts can then be aged to develop, by precipitation, optimum hardness and strength in the parent metal and across the joint. The same results can be obtained by solution heat treating and quenching the part in a separate operation after the brazing operation.

It is important that aluminum joints be thoroughly cleaned of all grease or oil films and dirt preceding the brazing operation. If a part has been annealed for forming, it should be cleaned by an etching method.

Corrosion resistance of aluminum brazed joints is comparable to the resistance of welded joints in the same alloy.

A valuable paper, "The Flow of Metal in Brazing Aluminum," by

M. A. Miller, was published in the *Welding J.*, pp. 472S-478S, October 1941, from which the following is quoted:

Because the oxide on aluminum surfaces is generally displaced rather than completely dissolved by the flux, it is usually advantageous to feed the alloy from one side of the capillary; this tends to overcome flux entrapment and porosity because the molten alloy has a better opportunity to sweep out the flux and particles of oxide and other surface impurities. A fairly large reservoir at the edge of the joint is generally desirable, so that the brazing alloy will have a chance to puddle and feed into the joint.

In the use of the new duplex aluminum brazing sheet . . . the situation is considerably different, for example, than the use of copper plating on steel. In the latter case, a hydrogen atmosphere is generally employed as a "flux," no flux-entrapment problem ensues, and long laps can readily be made. In the case of duplex brazing sheet, a flux being required, long laps are not generally permissible. In fact, the best joints are produced from line contacts; thus, the alloy coating flows vertically up or down or horizontally toward the nearest capillary space — and this, through surprisingly long distances — to fill the joint and produce a fillet of a size related to the type of coating, the thickness of the coating, the distance of flow, the temperature, and the time.

Capillary traps (enlargements in the capillary to overcome the effect of surface tension) are of little use in the brazing of aluminum. There are several reasons for this. The aluminum brazing alloys are somewhat more viscous than some of the non-aluminum brazing alloys, though they are still free flowing, and hence will bridge substantial gaps. Secondly, the aluminum brazing alloys, being intersoluble with the aluminum base metal, will exhibit surface creeping or flow; this process also results in a disregard for traps.

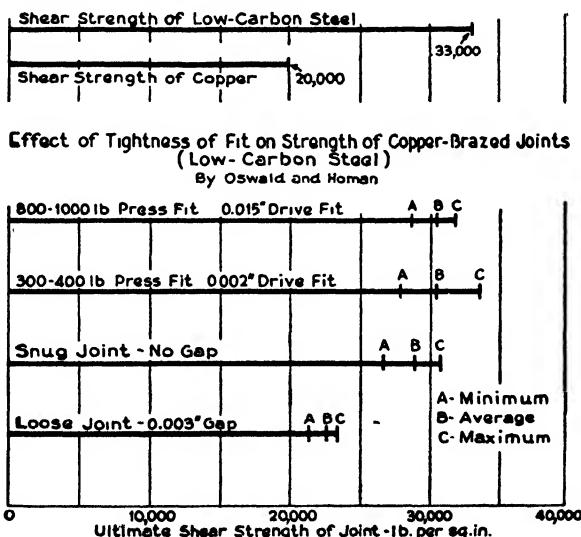


FIG. 16.9. Chart showing the effect of fit tightness on the strength of copper-brazed joints made from low-carbon steel.

**16.8. Joint Designs.** Since the filler metal is normally weaker than the parts joined by brazing, the strength of a brazed joint usually depends on the amount of unchanged brazing alloy left in the joint in the form of a thin coating. In turn, this depends on the composition of the filler and the parts, the time and temperature of the brazing operation, and the clearance in the joint. Provided the gap is not too great for the alloy to fill it, the strength of the joint approaches the strength of cast filler alloy as the gap is increased in any type of joint. Fig. 16.9 and 16.10 illustrate the effect of clearance on the strength of joints brazed with copper and

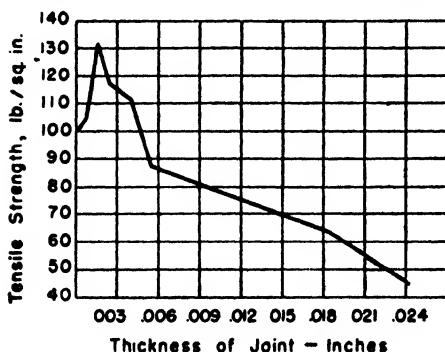


FIG. 16.10. Graph showing the effect of joint thickness on the strength of silver-brazed joints.

with silver. The clearances usually recommended for each of the four types of brazing alloy are given in Table 16.3.

TABLE 16.3. CAPILLARY CLEARANCES FOR VARIOUS BRAZING SYSTEMS

<i>Brazing Alloy</i>	<i>Base Metal</i>	<i>Recommended Clearance in Inches</i>
Copper	Ferrous	Press fit, <sup>1</sup> when brazing in a protective atmosphere
Copper	Stainless steel	0.0015 when brazing in a protective atmosphere
Silver alloys	Ferrous	0.0015 to 0.002
Silver alloys	Stainless steel	0.0015
Silver alloys	Copper, nickel, and their alloys	0.002 to 0.003
Aluminum alloys	Aluminum alloys	Approximately 0.025 for long laps <sup>2</sup>
60-40 Brass	Iron and copper	0.030
Tobin bronze	Ferrous	Open "V" joints

<sup>1</sup> For this purpose a good general rule to follow is to call for a maximum permissible press fit of about 0.001 inch per inch of diameter, allowing whatever tolerance the shop needs in the other direction.

<sup>2</sup> When using Brazing Sheet and when the coating is in the joint, the surfaces should make contact since the coating provides sufficient clearance.

The three fundamental types of joints are butt, scarf, and lap or shear (see Fig. 16.11a, b, c). Each may be used with flat, round, or tubular members. Butt joints are satisfactory when carefully made, and are sometimes the only way a joint can be assembled. An impor-

tant use of the butt joint is in the production of hollowware articles which are made by stamping half sections from sheet metal and joining

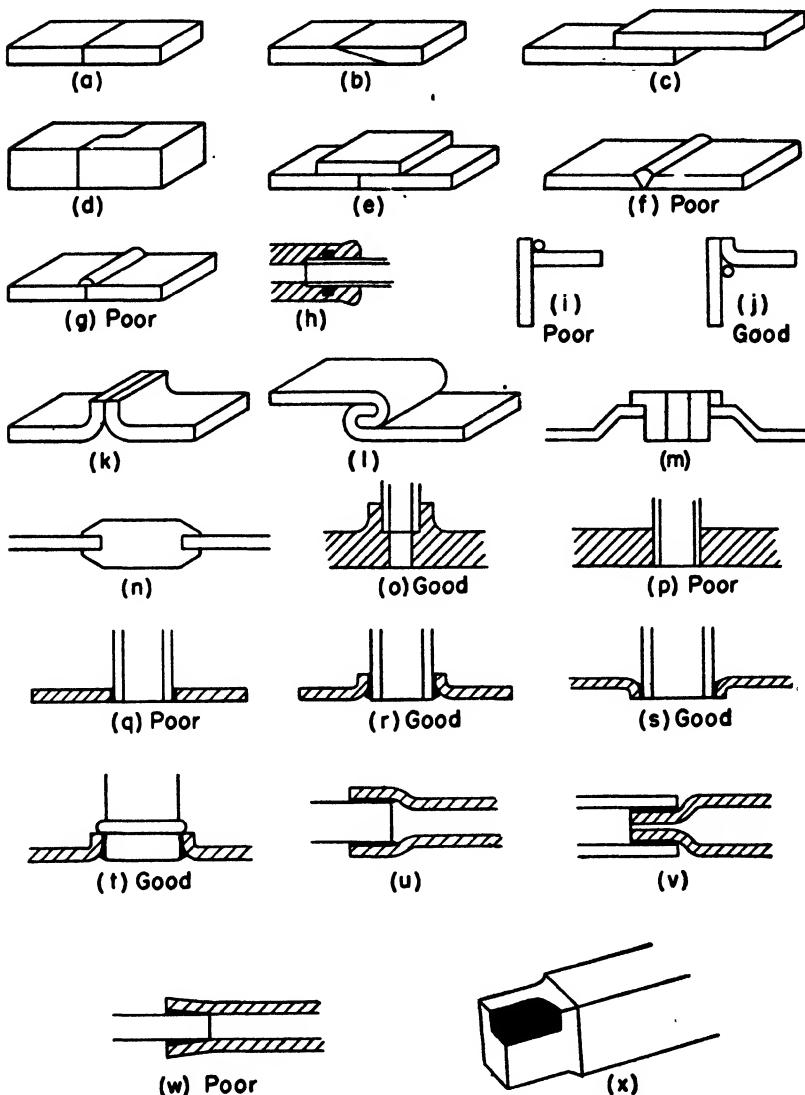


FIG. 16.11. Examples of good and poor joints for brazing, particularly with copper and silver alloys.

them. The edges must be square and straight to maintain a uniform space between the members and they should be held closely together to

insure even flowing of the filler metal by capillary action. When butt joints are necessary, greater strength can be obtained if a step or scarf type of joint (Fig. 16.11*d* and *b*) can be formed. The butt strap shown at *e* forms more of a compromise. The joint illustrated in Fig. 16.11*f* is used for spelter or bronze brazing and is not recommended for any other type of brazing.

Lap joints (Fig. 16.11*c* and *h*) are preferred for all types of brazing when high strength or pressure tightness is required. By increasing the amount of lap (area of the joint), any safety factor against failure may be obtained. When joining flat sheets or strips of copper, brass, or Everdur with silver alloys, a length of lap equal to the thickness of the sheet may give a joint as strong as the metal joined. However, for equal electrical conductivity of joints in copper, tests have shown that a lap equal to one and one half times the thickness is the safe rule to apply when using Sil-Fos.

It should be evident that the large number of factors which affect the strength of a brazed joint makes it very difficult to give a precise formula for determining the length of a shear or lap joint for some required strength. Fortunately, however, the strength of brazed joints is great enough that ample factors of safety can be provided and the length of lap still be kept within the limits of good and economical design. The following simple formula can be used for determining length of lap (depth of shear) on either tubular or flat joints.

$$X = \frac{YTW}{L}$$

where  $X$  = length or depth of shear,  
 $T$  = tensile strength of weakest member,  
 $W$  = thickness of weakest member,  
 $Y$  = factor of safety,  
 $L$  = shear strength of brazing alloy.

As an example, assume 50,000 lb per sq in. as the strength of the brazing alloy, and a factor of safety of 10. The length of lap for a copper tube with 0.064-in. wall thickness to be brazed in a pipe fitting (assuming the copper tube has a tensile strength of 33,000 lb per sq in.) is

$$X = \frac{10 \times 33,000 \times 0.064}{50,000} = 0.423 \text{ in.}$$

This equation applies only to the type of lap joints which distribute the load over the whole area. The type of lap shown in Fig. 16.11*j* and *k* is better than the joint shown at *i*, giving greater strength and

leak tightness, but mechanical load (tension) is all concentrated at one surface and so produces a tearing action which differs greatly from the condition existing in *c*, *e*, *h*, or *o*. The hub on the flange in *o* is recommended as an aid in heating. This is more important on heavy flanges.

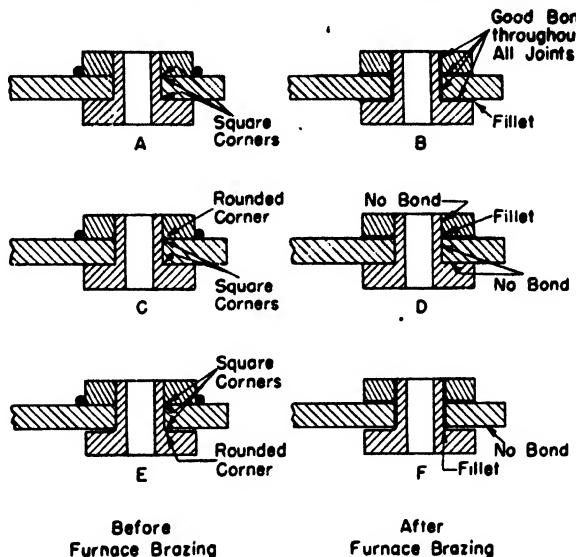


FIG. 16.12. Effect of gaps in the joint on the flow of brazing alloy.

Without the hub, the whole flange must be brought up to temperature to make a brazed joint. This might be satisfactory in a furnace, but most piping jobs are heated with portable equipment, and heating the whole part would be inconvenient.

The importance of clearance between parallel surfaces has been stressed but the same rule must be applied if filler metal is to flow around corners. Fig. 16.12 illustrates how gaps in the joint may block the flow of brazing alloy through the joint. Likewise, a square edge on the hole pressed tightly against a radius on the fitting as at *E*, Fig. 16.12, would stop the flow of a silver alloy, even though the clearance is right on each side of the corner.

It is very difficult to obtain a good joint that seals a cavity because of the pressure built up during heating as the air attempts to expand. Especial difficulty is encountered if a large volume of air must be heated.

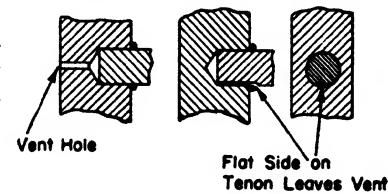


FIG. 16.13. Venting of cavities.

When possible, such cavities should be vented (Fig. 16.13). If a hermetic-seal is to be obtained, use of an eutectic alloy will provide quick setting and diminish the duration of the mushy period when leaks could occur.

When making flat joints in cable, the pressure applied may cause the strands of the cable to spread out. One of the many different methods used to control this is illustrated in Fig. 16.14. A piece of copper strip is formed to encircle the strands. Many such joints are brazed in spot

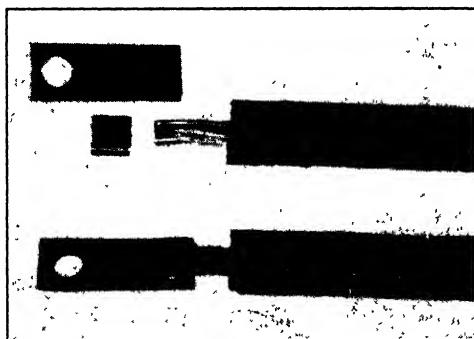


FIG. 16.14. Silver-brazed lead and terminal assembly for a transformer before and after brazing.

welders. The terminal is laid on the lower electrode, the cable carrying the ring or clip is placed with the opening next to the terminal but with a strip of Sil-Fos between. When pressure is applied the clip is flattened, and the opening allows Sil-Fos to flow up into the strands, making a solid connection. Larger cables that require longer heating are sometimes enclosed in pieces of regular copper tubing. The tubing will flatten to some extent in the brazing operation if brazed by an electrical resistance method, but many times is flattened in advance as a separate operation. When tubes are used, the filler is fed into the end of the strands by hand. Just enough is used to seal all the strands at the end without allowing excess alloy to creep back to stiffen the cable beyond the terminal. Another common method of binding the strands of a cable is to wrap them with wire or copper strip — 0.010-in. by 0.125-in. copper has been used for this purpose. The flat binding not only looks better than the wire binding, but with electrical resistance heating makes better contact with the electrodes to carry both electricity and heat. However, these wrappings are not as neat as the clips and tubes described.

**16.9. Joints Preloaded with Brazing Alloy.** One of the most fool-proof methods of placing the brazing alloy for any and all methods of

heating is to insert it in wire form in grooves, as shown in Fig. 16.15. This same method is employed in Wallseal pipe fittings to be used with copper and brass pipes. The assembly illustrated on the left is ideal for copper brazing in the controlled atmosphere furnace, but some clearance would have to be provided for alloy fillers. Fig. 16.16 illustrates several other ways of applying filler material in wire form. The staking is suggested especially to hold the parts for furnace heating. Also illustrated is a common method of loading rectangular wire or strip material. Fig. 16.17 shows two successful methods of using copper foil in furnace brazing.

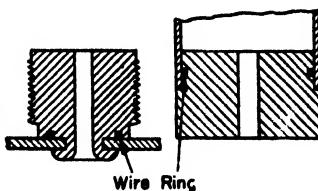


FIG. 16.15. Brazing wire inserted in a groove in the joint.

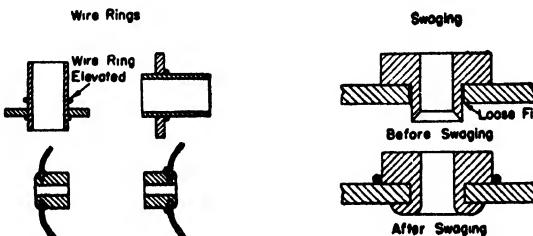
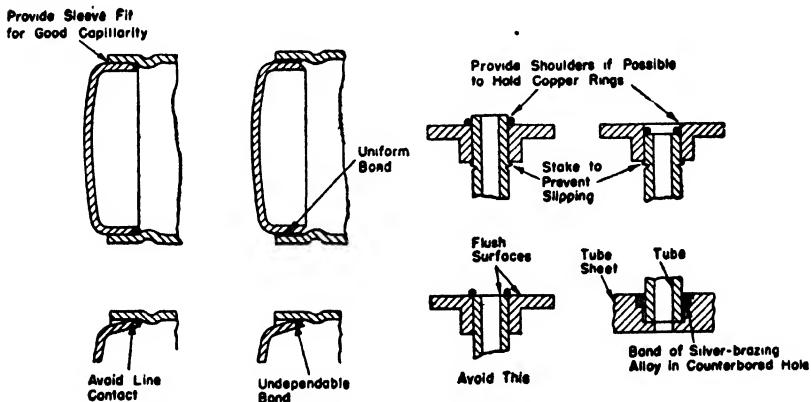


FIG. 16.16. Methods of applying brazing material in wire form.

The more common types of assemblies used in the brazing of aluminum are illustrated in Fig. 16.18.<sup>1</sup> These show the use of wire, coated

<sup>1</sup> From Technical Data Bulletin No. 3 of Aluminum Company of America.

brazing sheets, and one assembly using washers. As explained before, the aluminum filler metal is highly viscous, which explains why the tapered pipe fit is used. The filler for this fit would be a ring of wire. It is important that such wire rings hug the vertical surface and it is preferred that they grip the vertical surface tightly enough to hold them off the horizontal surface. This assures wetting of the vertical surface to form a good fillet, whereas if the ring lies on the horizontal surface, it may melt and flow away without bridging the joint. The taper fit is to be avoided with other kinds of filler materials.

Foil Inside of Joint

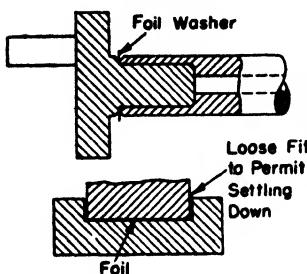


FIG. 16.17. Two methods of using copper foil in furnace brazing.

adapted to the particular situation, will aid the brazing operation in three ways: (1) It will coat the surfaces of the joint to protect them from oxidation by the atmosphere while heating; (2) it will dissolve

**16.10. Brazing Fluxes.** A flux is a chemical agent which, when properly applied and

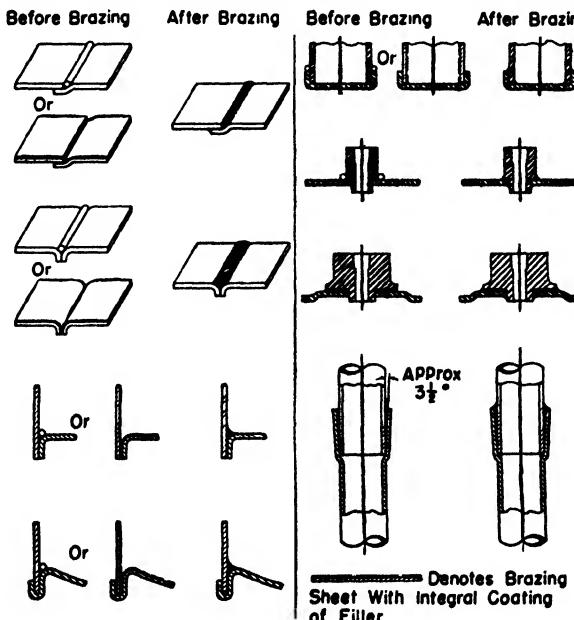


FIG. 16.18. Joint designs especially for aluminum brazing (*courtesy Aluminum Company of America*).

any oxides which have formed on the surfaces of the metal parts; (3) it will lower the surface tension of the molten alloy to allow it to flow more freely into the joint.

Brazing fluxes are not really active to perform functions 2 and 3 until the flux has melted.

It is emphasized that fluxes are not cleaners. At times a fluid active flux will function to produce a good joint under the handicap of dirty surfaces, but fluxes are not designed to remove oil, grease, carbon, paint, or many other kinds of dirt. Any oxide or dirt on the surfaces of the joint before the flux is applied only increases the chance of obtaining a poor joint. To assure the best results in the brazing of a joint, or to obtain uniformly good results in a series of joints, have the joint surfaces and adjacent areas clean and bright when the flux is applied.

Borax, which is the old standard flux for brazing, exists in two forms. Ordinary borax is in the crystalline form, containing considerable moisture in the form of water of crystallization. When heat is applied to this, it puffs up and rolls around so that it furnishes little protection to a joint being brazed. The use of amorphous, or fused, borax avoids this trouble, as it melts quietly. Its usefulness, however, is limited in two ways: (1) It melts at approximately 1400 F so is serviceable only with the higher melting point filler metals; (2) it does not dissolve the oxides of many of the alloying elements such as chromium, molybdenum, silicon, and tungsten so is serviceable only on the common steels, brasses, and bronzes.

Most brazing fluxes are mixtures compounded to obtain a lower melting point than that of borax, and a more active solvent for the refractory oxides. The type of flux needed is determined more by the base metals than by the filler. A flux stronger than necessary should not be used since the salts and fumes may be toxic and forced ventilation is required to remove them.

The dry powder fluxes are the most common, but they do not furnish as complete service as the paste fluxes. Paste fluxes can be brushed over the joint before heating, and so furnish some protection throughout the heating period. Paste fluxes also can usually be used in joints heated by electric resistance methods, whereas the electrical insulation resulting from the use of dry powder prevents its use in such applications. Paste fluxes are easily applied to other than horizontal surfaces. A gas torch also blows the dry powder away unless the surfaces have been heated to the point where the flux begins to melt and sticks. Often the end of the rod, or ribbon, of filler metal is heated so that the powder sticks when it is dipped into the can of flux. Sometimes the only flux

applied to the joint is applied along with the filler metal in this way. Although it is satisfactory on easy jobs, it is recognized as not the most effective way to handle a difficult situation.

Corrosion is a problem that seems always to be with us. Any residual flux that remains on the work after the braze is finished is apt to absorb moisture from the air and start corrosion the same as table salt would. The preferred practice, therefore, is to remove all flux residues.

A furnace atmosphere of hydrogen also acts as a flux to reduce the oxides of the iron, copper, and some other metals, but when the hydrogen does not function to reduce more refractory oxides, one of the regular brazing fluxes must be applied to the joint for this purpose. The salt bath described later as a heating method also serves as a flux. Aluminum requires special fluxes.

**16.11. Methods of Heating.** Almost any heating device that will raise the temperature of the joint to the necessary brazing temperature can be used, but economics and results obtained do place a few limitations on the choice of equipment.

The heating problem may be outlined by three requirements:

(1) Both members, or surfaces, of the joint must be heated above the melting temperature of the filler metal before it will wet and flow to make a good joint. The quicker the inner surfaces can be heated to the necessary temperature without overheating an external surface, the more satisfactory is the whole result. This problem is illustrated by trying to furnace braze a light aluminum section to a heavy section. The light section may overheat and slump before the heavy section reaches brazing temperature. In torch brazing the flame can be concentrated on the heavier piece to reduce the time required, thus limiting oxidation and perhaps other trouble.

(2) The oxidizing or reducing influence of the heating method or atmosphere upon the joint surfaces, flux, or filler material is important because it may have a marked effect upon the results. For example, any hydrogen present at the red hot surfaces of ordinary tough-pitch copper will probably have an embrittling effect. Except for the effect of hydrogen upon tough-pitch copper, city gas, which contains hydrogen, or other reducing atmospheres are always preferred.

(3) The two parts being joined must be held in proper relation to each other during both heating and cooling, and must not be moved until the alloy is solid, otherwise the filler metal will be granular with cracks. Some assemblies are best heated in jigs or stationary equipment; other jobs, such as piping on board ships, require the most portable equipment.

No one heating method is best for all brazing applications. It is

therefore worth while to review the more common methods of heating, which include furnace, torch, metal bath, chemical bath, arc, induction, and resistance heating.

**16.12. Furnace Brazing.** The important feature that makes a furnace so popular for brazing is the controlled atmosphere which is almost universally used. A neutral gas may be used for brazing joints in copper without embrittling or oxidizing the copper, but for the best results a reducing atmosphere in an electric furnace is usually preferred (copper parts are made from deoxidized copper). Any of the brazing alloys may be used in a furnace, and the low-temperature alloys have been used to advantage on special jobs; but since hydrogen does not reduce the oxide of zinc, the filler metals most popular for furnace work are either pure copper or one of the copper-silver alloys, except for joining brass. For it a flux must be used.

The furnace is best adapted to the brazing of small high-production assemblies or to units involving many joints. For such parts, it gives a high production rate since many joints are brazed at one time. Complicated assemblies are sometimes best heated in a furnace to equalize thermal stresses, since progressively heating one spot after another in a structure will sometimes result in bad distortion, or the cracking of brazing alloy while it is still hot. For the same reason, it is sometimes important to heat a whole structure uniformly in a furnace to make a single joint. Other benefits which may result from furnace brazing include the following: (1) Reduced production costs because of savings in time, material, rejections, or inspection; (2) uniform tightness as a result of uniform distribution of brazing metal, and through accurate control of time, temperature, and furnace atmosphere; (3) little or no distortion, with freedom from localized strains; (4) excellent appearance with clean, bright surfaces and smooth fillets at joints; (5) flexibility through ability to braze light parts to heavy ones, and to join unlike metals.

There are a variety of furnace designs (e.g., box type, mesh belt, and roller hearth conveyor types) to suit the requirements.

Hydrogen gas at temperatures above 800 C will reduce the oxides of carbon steel and copper, and when copper is heated above its melting point in contact with carbon steel in a reducing atmosphere, the copper will flow freely on the surface of the steel and will alloy with it. Furthermore, in the presence of a reducing atmosphere, the capillary action of liquid copper between two pieces of steel in close contact is very pronounced.

Since the process must be carried out in a hydrogen or other type of reducing gas atmosphere, the work is limited to assemblies that can be

heated in a furnace. It is true that copper brazing can be carried out with the use of suitable fluxes in air, using a gas torch or other methods of heating; but, owing to the high temperature required for melting copper and to trouble from oxidation, it is seldom done.

In copper brazing, the assemblies are put together, and the parts located by means of spot welding, pressing, swaging, etc., to prevent slippage or moving of the assemblies while the copper is in a liquid state. Copper, in some such form as wire, is applied near the joint and the complete assembly is then passed into an electric furnace at a temperature of approximately 1140 to 1150 C. After the copper melts and flows, the assemblies are passed into a cooling chamber where the copper-iron alloy formed at the joint solidifies and the whole parts cool to approximately room temperature.

The furnace brazing of aluminum requires that a special flux be applied in the joints as they are assembled. The melting point of these filler metals is so near the melting point of the parent metals that care must be exercised not to melt the filler metal or thin parts of the assembly before heavy sections are up to temperature. On the other hand, slow heating usually results in excessive oxidation, or an interdiffusion of the filler and base metal before the former flows freely. In designing for brazing, it is poor practice to combine a large range of thicknesses in the same assembly. Material 0.006 in. thick will reach brazing temperature in a few minutes, whereas it requires 40 to 45 min for  $\frac{1}{2}$ -in. material to reach temperature. A period of 2 to 6 min at the brazing temperature is required to melt the filler metal and flow it into the joints.

**16.13. Torch Brazing.** In the hands of an experienced and skillful operator, the gas torch is probably the handiest and most universally applicable method of heating. A combination of fuels, such as oxy-acetylene, oxyhydrogen, oxy-city gas, or natural gas are most commonly used. The heat is applied to the parts away from the joint in such a way as to bring both members up to the brazing temperature uniformly. A neutral or reducing flame is always used except when brazing tough-pitch copper; here an oxidizing flame is used to avoid embrittlement. A multiple tip torch is often used to speed operations. A variety of such tips are shown in Fig. 16.19.

**16.14. Metal Bath Brazing.** The metal bath brazing process is a dip process wherein the filler metal is obtained from the molten metal bath. For a number of reasons, it is confined to joining comparatively small work such as joints in wire.

**16.15. Chemical Bath.** This method of heating, also known as the salt bath, requires that the assembled parts, with the brazing alloy in place, be carefully supported by suitable jigs. The entire assembly is

then dipped into a bath of molten flux held at a temperature somewhat above the melting point of the filler material. It has the advantage of heating the members quickly and at the same time providing protection from the oxidizing effect of the atmosphere. Temperature is easily controlled in this process, which has shown considerable promise for the brazing of aluminum. The size of the bath will depend upon the size and weight of the assemblies that are to be brazed, but in general these baths should be large enough so that there is no appreciable drop in the temperature of the bath when the assembled units are immersed.

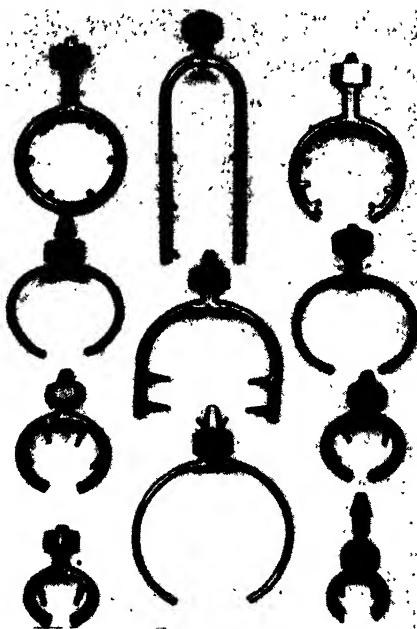


FIG. 16.19. Torch tips for silver brazing.

**16.16. Arc Brazing.** This is a process wherein the heat is obtained from an electric arc formed between the base metal and an electrode or between two electrodes. The carbon arc is perhaps the most common form, but the process is used very little in brazing.

**16.17. Induction Heating.** For many years it has been known that by introducing a metal part into the center of a coil carrying alternating current, the metal would be heated.

Application of this type of heating has been limited by the equipment available, but recent developments are leading to much more general applications, including brazing and soldering as well as other heating

jobs. It is the one method of heating which always generates all the heat within the parts being heated, in contrast with the methods which heat from the outer surface. Many brazed joints are of a type to which induction heating is readily applied. For such joints, one or more of the following advantages may be obtained: (1) Short heating time; (2) lower costs; (3) semiskilled operators can be used; (4) heat is confined to a small area around the joint, and the assembly can be easily handled by workers; (5) small amount of scale; (6) the heating operation can be controlled automatically to produce uniform results; (7) no hazard of flame.

Motor-generator sets, which have been developed to supply power at frequencies up to 12,000 cycles per second, have a wide application in the heating of relatively large steel parts. The low frequencies, however, are not economical for the heating of copper, aluminum, and small irregularly shaped brass and steel parts. A spark gap oscillator has been developed to supply the higher frequencies for heating these parts, but it is limited to about 200 kilocycles and approximately 15 kw power output. Electronic heaters (vacuum tube oscillators) to supply power at 550 kilocycles are now developed and built to industrial standards and their use and applications are expanding rapidly.

The fundamental principle in heating a part to be brazed is to create an alternating magnetic field into which the joint may be placed. In practice, the joint is positioned in the center of a specially fitted coil and high frequency alternating current is applied for a definite time cycle. For best results the coil shape and size should match the assembly to be heated. A coil is easily made from copper tubing which carries its cooling water.

To achieve high production in induction brazing operations, more than one joint can be heated at a time by connecting a number of coils in series. Fig. 16.20 shows such an installation for brazing the four terminals simultaneously to the low-voltage conductors of a transformer. The installation forms a station on the production line.

Any joint properly designed for brazing and of a shape such that an induction coil can economically be designed around it can be successfully induction brazed. When possible, the joints should be designed for pre-assembly with the brazing alloy in position prior to heating. Usually it is important that the alloy as well as the parts be thoroughly fluxed. Fig. 16.21 shows several types of joints that have been successfully induction brazed and illustrates the application of the heating coils. The same capillary clearance must be allowed in joints such as *A*, *B*, *C*, and *K* as has been discussed before and as listed in Table 16.3.

In press type joints such as *D*, *F*, and *J* an allowance of 0.0005 to 0.001 in. is sufficient.

The close control of temperature-time cycles often makes it possible to complete a joint without affecting the finish on the parts. Silver plated parts have been brazed successfully without harming the plating, and even with copper, the oxide film is very light on account of the speed of heating and cooling. Flux will protect the surface near the joint when a bright surface is desired after brazing. With the better installa-

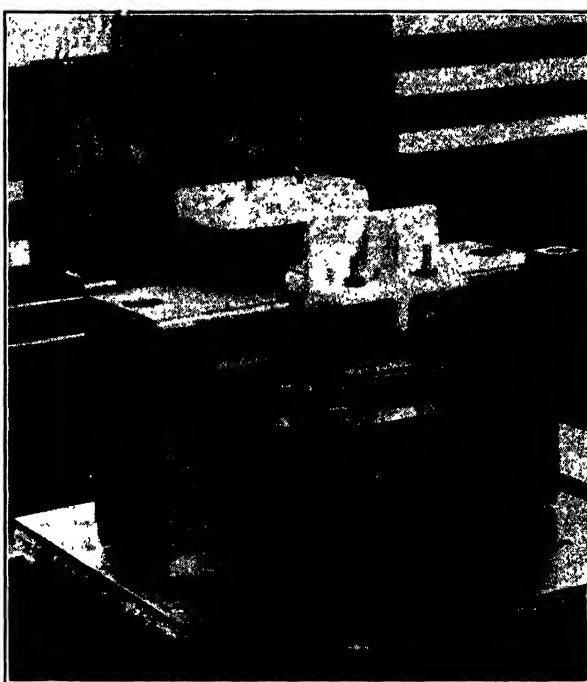


FIG. 16.20. Installation for induction brazing four terminals to the low-voltage conductors of a transformer. The induction furnace is at the top.

tions, power is applied by a pushbutton and stopped automatically by a timer.

**16.19. Resistance Brazing.** Resistance brazing is an electric brazing process wherein the heat is obtained by passing an electric current through the parts being brazed. There are two rather distinct types of equipment used: (1) that using carbon blocks and (2) regular resistance welding machines.

When carbon blocks are used for electrodes, they are heated to a

bright temperature by their electrical resistance, and most of the heat obtained in the joint is conducted in from the hot carbons. The equipment may be either stationary or portable. Fig. 16.22 shows a complicated assembly being brazed in a stationary press using carbon blocks for heating. The working faces of the press are water cooled. Fig.

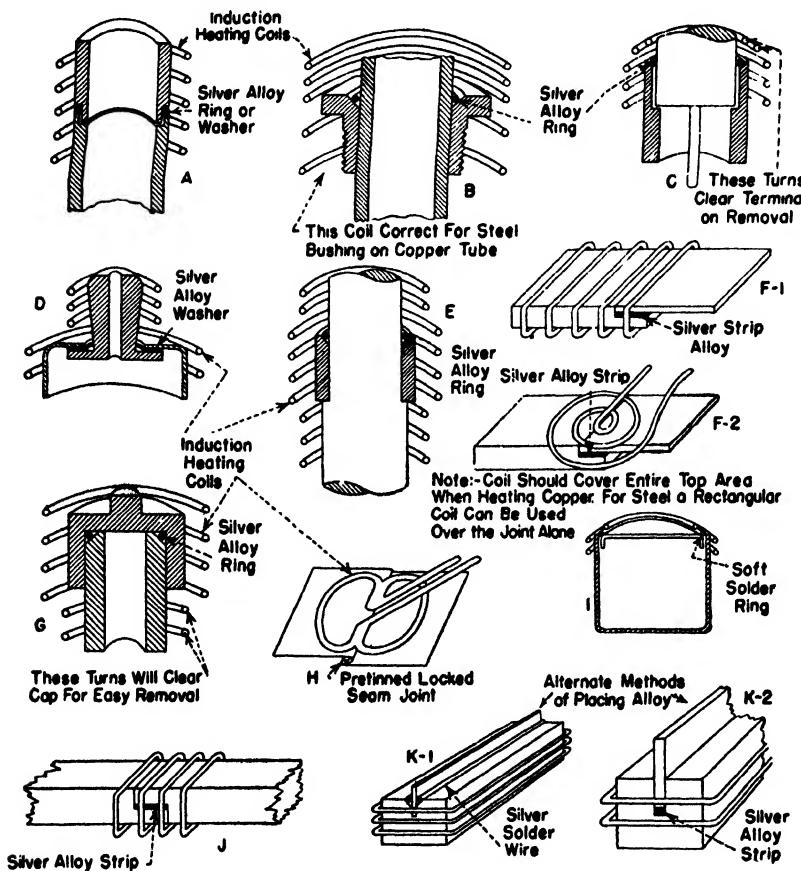


FIG. 16.21. Joints for induction brazing, and the application of the induction heating coils.

16.23 shows a joint gripped in portable equipment for brazing. Such an outfit usually employs 5, 10, or 20 kva high-current low-voltage air-cooled transformers, but smaller or larger water-cooled transformers are used for certain jobs.

Resistance welding machines with their accurate timers give fine results and high speed on many small part assemblies. They are

especially useful with assemblies of copper and copper alloy parts where Sil-Fos can be used, such as putting terminals onto cables. Fig. 16.24 shows how a small piece of copper is placed to confine the strands of the cable brazed to the head of a brass screw. Sil-Fos with a small amount



FIG. 16.22. Four braid groups in clips being silver-brazed simultaneously to a fabricated conductor. Carbon blocks are used for resistance heating.

of paste flux is used on brass. Pressure is maintained on the joint until the alloy is solid; then as soon as pressure is released the hot joint is quenched in water to remove the flux and save the insulation. The result is a clean, neat joint with a minimum amount of heat effect.

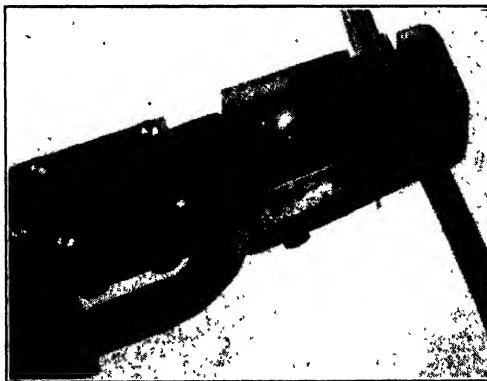


FIG. 16.23. Portable electric resistance brazing tongs being used for brazing a conductor stack.

With certain size sections of copper cable, this is the only way in which satisfactory silver brazed joints can be made without burning the insulation or unduly annealing the copper.

Such machines are equipped with electrode surfaces of tungsten or

some high-tungsten alloy backed by water-cooled copper, so that a great deal of the heat is generated in the joint. The water cooling produces quick solidification of the alloy. The heating time for small parts may be only  $\frac{1}{2}$  sec and seldom exceeds 3 sec for the largest joints such as terminals onto 250,000 cir mil cables. A coil of the brazing alloy ribbon is frequently mounted by the electrodes so that it is always handy and is assembled in, or fed into, the joint without cutting or waste.

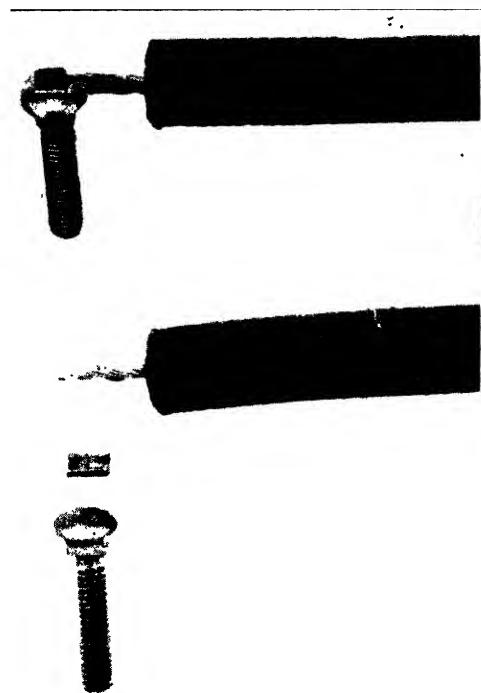


FIG. 16.24. Silver-brazed primary lead assembly for potential transformer, before and after brazing.

Resistance brazing usually has the following advantages: (1) Heat under pressure. Electrode faces may be flat or formed. (2) Rapid heating and cooling. (3) Easy control of heat. (4) Reduced hazard of flame. (5) Easily adapted to unskilled help.

Many transformer assemblies are completely brazed with carbon blocks except for the detachable leads. Some of the joints are made so close to insulation that a gas torch for heating would be a real hazard.

Resistance seam welders have been used to a limited extent to braze

seams between copper parts using Sil-Fos in the joint. It is claimed that such joints can be made between parts of hard copper, with the flood of cooling water common to seam welders, resulting in very little annealing or loss of physical strength.

**16.20. Final Cleaning.** Sometimes the removal of flux residues becomes a real problem. Although fused borax need not be removed as a corrosive agent, it should be removed from surfaces to be painted. All common brazing fluxes are water soluble, and the hotter the water, the faster the cleaning. It is a great help if the joint can be immersed in a tank of hot water. Probably the next best method is to apply water to the joint while it is still hot, about 400 C. If the part cannot be immersed, the application of a wet cloth that will confine the steam for a minute or two is a help. A jet of live wet steam is also effective. If there is any objection to the use of water, the sand or grit blast or emery cloth is about the only satisfactory method of removing the flux residue. Even if it is chipped and scraped off by hand, a damp cloth is usually necessary to finish the job. Some of the fluxes are very hygroscopic and become damp and sticky after setting in a damp atmosphere.

## SOLDERING

By R. S. PELTON

**16.21. Definition and Application of Soldering.** Soldering is a method of uniting two or more pieces of metal by means of a fusible alloy or metal, called solder, applied in the molten state. The soldering process is distinguished from brazing in two ways. First, lower temperatures (below 1000 F) are used, and second, there is less alloying between the filler and the metals united, the strength of the joint depending upon adhesion. Lead and tin are the bases for most solders. Since they are of low strength, and because of the nature of the bond, the joint should be designed so the solder is not depended upon to carry much load. The solder should serve primarily as a filler material to stop leaks in mechanically locked seams, to seal joints against corrosion, and to carry electricity. It is also a convenient means of tying the strands of conductors together, of filling cavities, and of forming large fillets in sanitary equipment to facilitate cleaning. Lead pipe and cable sheathing may be joined by a wiping technique in which a thick layer of solder is applied and, when still in the mushy state, is smoothed out or wiped into a streamlined form.

**16.22. Solders.** Probably hundreds of alloys have been produced and used in the past. The scarcity of tin caused by the war led to the development of a few more and has resulted in other rarely used formulas

coming into common use. Although a hundred compositions could be listed that are recommended for various uses, the more commonly used solders are listed in Table 16.4. Others for special purposes, such as the soldering of aluminum, are marketed under trade names. Very few technical data have been published regarding them individually.

**16.23. Strength of Soldered Joints.** The room temperature shear strength of soldered joints may vary considerably because of differences in (a) the gap or clearance in the joint, (b) the soldering temperature, (c) the duration of heating, and (d) the base material soldered. Their

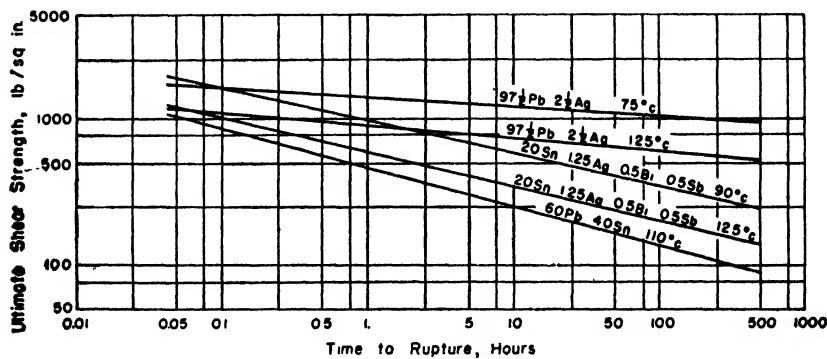


FIG. 16.25. Rupture shear strength of soldered joints 1 in. square under long time loading at elevated temperatures.

strength also depends to a large extent upon the temperature. Fig. 16.25 shows the results of rupture tests under long time loading conducted to show the strength of some common solders at the elevated temperatures commonly encountered in operating electrical apparatus. The joints tested were each 1 sq in. in area and loaded in shear. The lead-silver alloy stands out as being the most reliable for service at elevated temperatures. It is, however, sluggish in wetting and flowing, besides requiring a higher temperature for its application. For these reasons it is not generally used, but does serve important applications such as holding binding wire on motor armatures which operate at elevated temperatures.

Still another effect leading to a reduction in strength with increased temperature is the increased tendency for diffusion of tin (in tin-containing solders) into copper joints.

**16.24. Design of Soldered Joints.** Butt joints of any description are prohibited. Lap joints loaded in pure shear may be used if proper clearance is allowed. Care should be used not to subject the solder to a peeling action.

TABLE 16.4. SOTI SOLDERS

Pb	Composition in Per Cent			Degrees C			Degrees F		Remarks
	Sn	Ag	Bi	Sb	Soften	Flow	Softening	Flow	
1	97.3	2.5			304	304	580	580	High strength at elevated temperatures, sluggish.
2	90	10			224	300	435	576	Low cost, not so free flowing, used in dip pots.
3	87.5	10	1.5	0.5	0.5	290			Ag, Bi, and Sb improve strength and wetting and flow qualities.
4	80	20		1.25	0.5	183	285	360	
5	77.75	20		1.25	0.5	178	270	351	Low tin, general-purpose.
6	66.75	30		1.25	2.0	183	260	360	Low tin solder for wiping joints.
7	60	40				183	238	360	The preferred general purpose solder.
8	50	50				183	212	360	
9	37	63				183	183	360	Eutectic, high fluidity.
10		100				232	232	450	Used when available for pre-coating and joints in electrical conductors.

Clearances of 0.001 to 0.010 in. are permissible, but best strength and ease of soldering are obtained with about 0.003 in. clearance. When free alloying may occur between the base metal and the filler, the change in the composition of the filler may be sufficient to noticeably change the fluidity or the melting point of the solder. This leads to difficulties in the soldering and for such alloys may favor larger clearances.

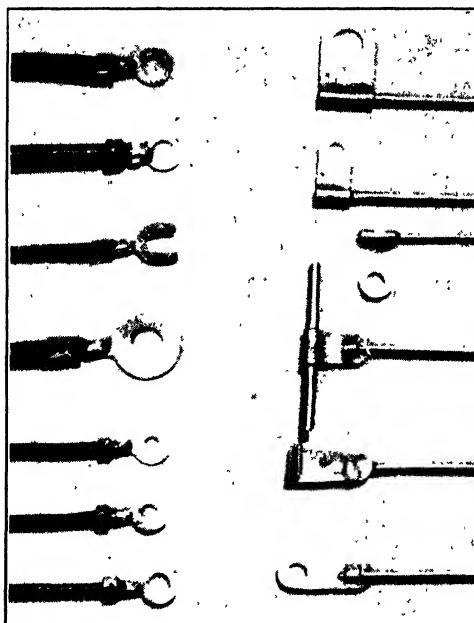


FIG. 16.26. Samples of soldered wire terminations.

The solder itself in a joint should not be placed under any greater mechanical load than is really necessary. In thin sheet metal, lock seams should be used. Wires should be hooked, clamped or clipped whenever possible. Fig. 16.26 shows a variety of wire terminals. When insulated stranded wires are used, one pair of fingers on the terminals grips the strands of wire while another pair grips the insulation. Solid wires are likewise secured before soldering. A good rule is to fasten the parts so that they will stay in position and hold the required load, without the solder before the solder is applied. As with brazing, the parts should not be allowed to move while the filler is still in the plastic state or just below the freezing point; otherwise the filler will be granular with cracks.

Sometimes the solder must be depended on to carry some load. Area

enough can frequently be obtained with lap joints in plain shear to make such joints safe. Fig. 16.27 shows the maximum shear stress allowable on soldered copper joints as determined by long time rupture tests. It was found that soft soldered joints are not reliable beyond the range shown by the respective curves. The tin-antimony solder possesses higher strength than other solders at low temperatures but is not reliable above 120 C regardless of load. The cause of failure in this case is not definitely known. It may be the combined result of diffusion and corrosion. As pointed out, these tests were conducted with soldered joints in copper. If steel or other materials had been used, the results might have been different. Also, the solders were the common ones before tin became scarce. Later results showed that 2½ per cent silver, 97½ per cent lead behaves similarly to the 5-95 alloy; also that 100 per cent tin behaves like the 95 per cent tin plus 5 per cent antimony solder. The curves in Fig. 16.25 may also be helpful in determining strength values, especially at elevated temperatures.

A common rule for electrical joints is: for strips  $\frac{1}{16}$  in. in thickness or less, a lap of  $\frac{1}{2}$  in. or more should be used. For strips more than  $\frac{1}{16}$  in. thick, a lap of  $\frac{1}{2}$  in. or more plus a clip around the joint should be used. Wide members may be riveted together instead of clipped. For cables or conductor groups terminating in tubular or similar terminals, the length inserted into the terminal should not be less than twice the diameter of the cable.

**16.25. Soldering Fluxes.** In preparing a joint for soldering, the first step is to insure absolute cleanliness of the surfaces to be joined. Do not depend upon the flux to clean the joint. Oil and grease should first be removed by a solvent; then the dirt and oxide should be removed by some means such as scraping, pickling, grit blasting, or scrubbing with emery cloth or steel wool. If large areas are to be joined, it is best to precoat them with either solder or pure tin. This is not so important

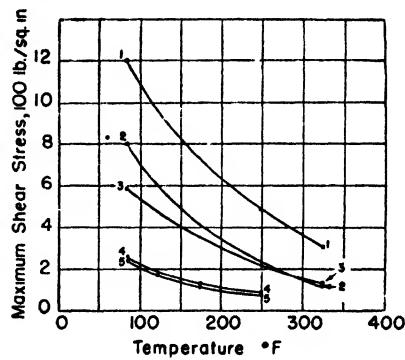


FIG. 16.27. Maximum allowable shear stress vs. operating temperature for sleeve joints in copper tubes. Data are for long time rupture in shear.

Curve 1-1. 95% tin, 5% antimony solder.

Curve 2-2. 95.3% lead, 4.7% silver solder.

Curve 3-3. 95% lead, 5% tin solder.

Curve 4-4. 60% lead, 39% tin, 1% antimony solder.

Curve 5-5. 50% tin, 50% lead solder.

for small joints. It is always desirable to remove the flux residue after " pretinning " before assembling the joint for soldering or before placing the parts in stock.

The clean surfaces to be soldered should ordinarily be covered with flux before heat is applied, either for precoating or for soldering the final assembly. The choice of flux depends on the material being soldered. The fluxes serve the same three purposes in soldering as in brazing, but because of the lower temperature used, they are quite different. There are two general types, noncorrosive and corrosive. Although the different soldering fluxes are innumerable, a few of the more common fluxes, representative of the different types, are listed in Table 16.5.

The noncorrosive fluxes are usually organic products which begin to char and break down at about 300 C, so extra care must be used in heating when they are used with the high-lead low-tin solders. They are called noncorrosive because the residue left on the finished joint

TABLE 16.5. SOLDERING FLUXES

Description	Form	Suitable for	Remarks
NONCORROSION			
Rosin and alcohol.	Liquid	Copper, brass, tinned, cadmium or silver-plated surfaces.	General for soft soldering where surfaces are very clean.
Rosin and naphtha.	Liquid	Same as above	For slightly oily surfaces. Danger, very inflammable.
Analine phosphate.	Paste	Copper, brass, aluminum bronze, rolled zinc (not zinc die castings), carbon steel, nickel, and nickel alloys.	Most active noncorrosive flux available. Ventilation necessary for continuous work owing to toxic effect of gas released. Residue may be electrically conductive. Should not be used for braided copper wire connections.
CORROSIVE			
Zinc chloride, ammonium chloride plus water.	Liquid	Copper, brass, aluminum bronze, rolled zinc (not zinc die castings), carbon steel, nickel and nickel alloys.	A good general purpose liquid flux, but not suitable for work immersed in insulating oil or in contact with insulating materials.
Zinc chloride and petroleum.	Paste	Same as above	Use where paste flux is more convenient than a liquid.
Zinc chloride plus water	Liquid	Brass	An ammonia-free flux suitable for brasses to lessen the dangers of season cracking.
Acid type	Liquid	Stainless steel	Very corrosive

is not corrosive like the salt materials used in the corrosive type of fluxes. It is necessary that the residue from the latter type of fluxes be washed off to prevent corrosion in humid atmospheres. The corrosive fluxes are much more effective in dissolving oxides, and they are also apt to be electrically conductive.

**16.26. Methods of Heating.** As explained earlier, in order to have the solder wet metal surfaces, the parts must be heated to the melting temperature of the solder.

All the heating methods described for brazing are applicable for soldering, plus the old reliable soldering "iron" or copper. Although both the furnace and electric arc are used, they are not at all common. The chemical bath is represented by the hot oil bath which is used to flow thin tin coatings that have been electroplated on, and to remove excess tin or solder after the part has been dipped in a metal bath. Both methods produce the smooth shiny surface found on commercial tinware.

The soldering pot, filled with the molten solder, is commonly used both for precoating and for the soldering of assembled joints. The parts are prefluxed and immersed in the pot enough to insure complete heating. Molten tin will dissolve copper at temperatures below the melting point of copper, thus resulting in contamination of the tin in tin pots by copper leads.

Soldering irons, electrically heated and otherwise, are commonly used for the heating of light parts and thin sheet metal where the joint is accessible. Since the transfer of heat depends on good contact, the soldering iron operates best when a flat surface on it is held against a flat surface to be heated. The solder, usually in wire form, is then fed in between the two surfaces.

Gas torches are not as common for soldering, but because of the portability of the gasoline blow torch, it is popular with some tradesmen.

Induction heating is a quick, clean, easily controlled method of heating that is gaining in popularity for the type of production job where it can be applied easily.

Resistance welding equipment has been used for heating for soldering, but it is not common practice. Carbon resistance tools, however, seem to be gaining in popularity. Tongs may be used as in brazing, or a pencil or fork as illustrated in Fig. 16.28 may be used. Handles may be applied to forks or pencils in other directions to make them more adaptable. When a part is grounded to one side of the circuit, the application of the carbon pencil heats a spot quickly. The transformer is comparatively small and supplies a large current at low voltage. The fork and plier types of tools are used on joints where contact between the two carbon electrodes can be made by the joint to be soldered.

These introduce heat from two sides simultaneously, giving quick heating.

**16.27. Final Cleaning.** When a soldered joint is completed, it is usually desirable to remove any flux residue for the sake of good appearance, if not as a precaution against corrosion. Rosin is removed with a brush and a little denatured alcohol. Naphtha is also a solvent for rosin, but it is rather volatile and so is dangerous.

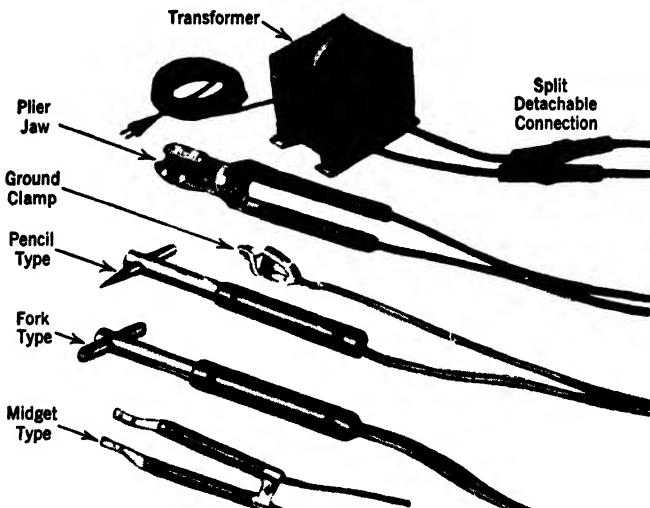


FIG. 16.28. Electric resistance soldering tools.

Whenever a flux is to be removed, it is valuable to know of what the flux consists. For example, many fluxes have a water-soluble salt suspended in grease. To remove such a flux thoroughly, a grease solvent should first be used, then a hot water wash to remove the final traces of the salt. Zinc chloride is a common constituent in soldering fluxes, both in grease and in water solutions; and it is similar to table salt in causing corrosion and in ease of removal with water. If the flux is a water solution, of either salts or acids, hot water is a quick safe means of removal if the water is clean. The water should be flowing with fresh water continually coming in or a dangerous concentration of flux may build up in the wash.

#### RESISTANCE WELDING

By R. T. GILLETTE and J. F. YOUNG

**16.28. Introduction.** In resistance welding, the metal parts to be joined are heated by their resistance to the flow of an electrical current.

Usually this is the only source of heat, but a few of the welding operations combine resistance heating with arc heating, and possibly with combustion of metal in the arc.

The constantly growing importance of resistance welding to modern industry is due mainly to the following advantages of the process over the other forms of welding:

- (1) It is faster.
- (2) It permits more accurately regulated application of heat.
- (3) Mechanical pressure is used to forge the weld, resulting in a grain structure and mechanical properties comparable with those of the parent metal.
- (4) No extraneous materials such as filler rods or fluxes are used, thus none of these are present to complicate the metallurgy of the weld.

The process applies to practically all metals and most combinations of them. Pure metals and those alloys which have only a limited plastic range are welded by heating the parts to fusion (melting). Some alloys, however, may be welded without fusion; instead, the parts are heated to a plastic state at which the applied pressure causes their crystalline structures to grow together. The welding of dissimilar metals may be accomplished by melting both metals, but frequently only the metal with the lower melting point is melted, and an alloy bond is formed at the surface of the unmelted metal.

Although the resistance welding process is best suited to mass production, it is also readily adaptable to low production and job-shop work when suitable equipment is available. With either type of production, work of uniformly high quality and relatively low cost can be turned out if full advantage is taken of designing the parts for the process. Since the different types of resistance welding equipment have some bearing on the design, they will be reviewed separately. Before this is done, however, a few principles fundamental to all the methods will be considered.

**16.29. Fundamentals of Resistance Welding.** The heat generated *in the weld* (when there is no arcing or combustion) may be expressed by

$$H = I^2 RT$$

where  $H$  is the heat,  $I$  the current,  $R$  the electrical resistance of the assembly, and  $T$  the time or duration of current flow.

All of the heat generated at the weld section is not used directly in raising that section to its welding temperature, because some heat is always conducted to the adjacent material, and some is transferred (by convection and radiation) to the surroundings. The amount lost from the weld section is lessened by decreasing the time allowed for making

the weld. The section adjacent to the weld should not be allowed to overheat, as distortion and surface discoloration may result.

In most applications, heat is also conducted to the "electrodes" which carry the current to the work and apply the forging pressure. Since these electrodes are already heated by the current flowing through them, they may soon reach a temperature at which they would no longer be strong enough to forge the weld. To avoid this, they are made from high-conductivity material, large in cross-section, and they are cooled by internal water circulation.

*Resistance.* The electrical resistance,  $R$ , in the above equation depends on the cross-sectional area through which current flows and is made up of

- (a) the resistance of the current path in the work,
- (b) the resistance at the contact surface (or surfaces) between the parts being welded (the work), and
- (c) the resistance at the contact surfaces between the electrodes and the work (when these may be considered a part of the weld section).

For welding most materials, resistance  $c$  should be kept as low as possible in order that the highest temperature will be reached at the interfaces of the work, rather than at the surfaces in contact with the electrodes. Resistance  $c$  is therefore usually much smaller than resistance  $b$ .

When welding thin materials, or materials which have a high conductivity, resistance  $a$  will be small compared with both  $b$  and  $c$ . This means that the heat generated will depend largely on the contact resistances, and for uniformity of the welds, this resistance must be closely controlled. In turn, this requires control of the surface condition of the material, that is, control of cleanliness, freedom from oxides and other chemical compounds, and of the roughness of the surface. In addition, the pressure must be controlled because it too influences the contact resistance; the greater the pressure, the lower the resistance.

The welding of thick materials or materials of low conductivity does not depend as much on uniformity of contact resistance because resistance  $a$  is comparatively greater than  $b$  and  $c$ . It should not be supposed, however, that consistent welding can be done in these materials without good control of surface conditions, even though this control is less critical than for thinner materials and for materials of higher conductivity.

In the welding of materials having very high conductivity, reduced pressures are sometimes used to increase the contact resistance. Only

limited use can be made of this effect, however, because the reduced pressure results in reduced forging action, and welds may show porosity in thick material or cracking in thin material if the pressure is reduced excessively.

Another technique for welding very high conductivity materials is to use high-resistance electrodes which have a melting point well above that of the materials being welded. These electrodes are used at relatively high temperatures so they conduct little heat from the weld. They may, in fact, be hotter than the work and thus conduct some heat to the weld section.

*Pressure.* The effects of applying pressure to the weld during resistance welding have already been mentioned. They are:

- (a) the forging action usually results in fine grain structure in the weld,
- (b) the pressure influences the contact resistance,
- (c) a large enough pressure permits making low-temperature plastic welds in some materials.

These last two effects are compensating. That is, a reduced pressure results in higher contact resistance and more heating, thus giving the higher temperature needed to weld at the reduced pressure. The range of compensation is narrow and easily exceeded, however, and too much reduction of pressure may require a longer time or more current to produce a weld.

Several factors complicate the problem of maintaining the electrode pressure. At the instant the weld is made, at least one electrode must move toward the other if there is to be any forging action. Although the amount of travel is small, it must be extremely rapid to be effective. The static friction between the electrode holder and its guides, and the inertia of the parts to be moved both oppose this rapid motion and thus lessen the electrode pressure. To lessen static friction, some machines have been designed that maintain sliding friction while the weld is being made.

Another factor that tends to reduce the available pressure is the inductive reaction between the arms supporting the electrodes. These arms are usually parallel and close together, and they carry current in opposite directions, thus setting up magnetic fields which tend to force each other apart. If only a few amperes of current were used, this tendency would be of little importance, but with current values of 10,000 to 100,000 amperes, the tendency to separate is very strong. In one application, the electrodes were applied to two pieces of brass each  $\frac{1}{2}$  in. thick with a pressure of approximately 1850 lb. The inductive

reaction reduced this pressure nearly 90 per cent during the time the current was flowing.

*Current and Timing.* Once the material, electrodes, and electrode pressure have been chosen, the only variables left which may be adjusted to control the rate of heating are (a) the amount of current,  $I$ , and (b) the time,  $T$ , that the current is allowed to flow. Large currents are needed and they are usually obtained from a welding transformer which "steps down" the voltage of an a-c supply. The secondary current or welding current which flows depends on the ratio of the secondary circuit voltage to the circuit impedance. The current can therefore be changed by changing either the voltage or the impedance. Since the impedance depends to a great extent on the fixed dimensions of the secondary loop circuit, it is more practical to vary the voltage for heat control. This may be done by (a) using taps on the primary of the

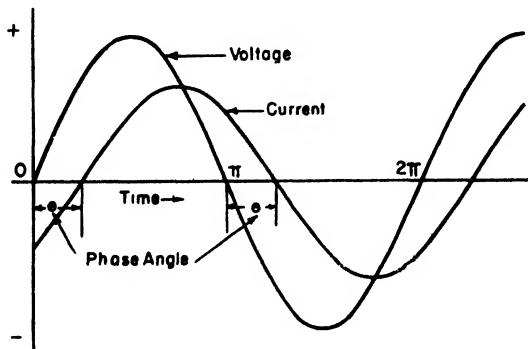


FIG. 16.29. Alternating current and voltage phase angle relations.

welding transformer so the number of primary turns may be changed, or (b) using an autotransformer which applies any of a range of voltages to the transformer primary.

Another method, and the one most commonly used to obtain heat control, is to control the wave shape of the current applied to the welding transformer primary. The supply voltage if continuously applied to the welding transformer would produce sine waves of current in both primary and secondary. Because of induction in the transformer, these currents lag behind the voltage by some phase angle, shown as  $\theta$  in Fig. 16.29. The magnitude and wave shape of the primary (and secondary) current can be altered by using Thyratron or Ignitron tubes in the primary circuit (see Fig. 16.30) to control the current flow. This is called *phase shift control* and is accomplished by causing the tubes to begin conducting current at predetermined positions on the

voltage cycle. Typical oscillograms of the supply voltage and respective primary and secondary currents obtained with this control are illustrated in Fig. 16.31. The use of phase shift control makes possible the elimination of expensive transformer taps and tap switches, resulting in

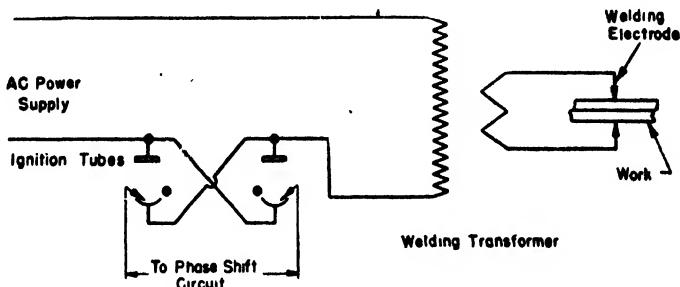


FIG. 16.30. Elementary diagram of a welding circuit using Ignitron power tubes.

a lower cost transformer with better operating characteristics. Another advantage of phase shift control is that it facilitates the addition of a current regulator to the circuit. Numerous types of timing controls are available for use with the Thyratron and Ignitron circuits.

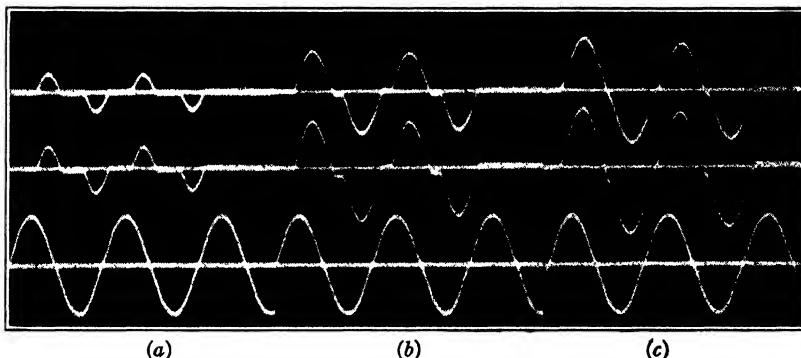


FIG. 16.31. Oscillograms of welder current with phase shift method of heat control. (a) For minimum heat (approx. 8%); (b) For moderate heat (approx. 55%); (c) For maximum heat (100%). The top curves show primary current, the middle curves secondary current, and the bottom curves line voltage.

The application of motor or other mechanical drive to welding machines has introduced cam- and gear-operated limit switches as a common method of timing. These switches operate solenoid contactors which control the actual welding circuit. They are an improvement over straight manual control but they still have several deficiencies which

make them unsuitable in some applications. The contacts wear rapidly, so maintenance costs are high, and the wearing results in an increased gap which in turn affects the timing. In addition, the switching is nonsynchronous.

By nonsynchronous switching is meant the closing of the primary circuit without respect to the value of the voltage at the instant of closing. If the point of closing happens to precede the power factor angle, a transient condition will result and several times normal current may flow for the first half cycle or so, as shown in the oscillogram in Fig. 16.32. It has been discovered that the heating effect of this transient (sometimes spoken of as a d-c component), especially on those materials requiring short welding time, may give more serious nonuniformity in

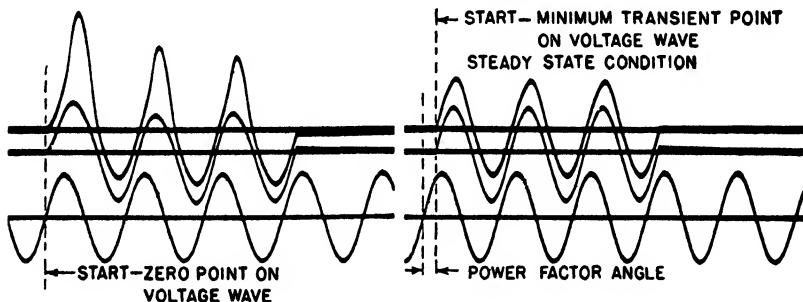


FIG. 16.32. Oscillograms of welder current showing the result of starting current flow at different points on the voltage wave.

(Left) For nonsynchronous switching of current at zero point in voltage wave.

(Right) For synchronous switching of current at power factor angle. The top curves show primary current, the middle curves secondary current, and the bottom curves line voltage.

welds than a short variation in time, and may even destroy the electrode surfaces or burn a hole through the workpiece. To avoid or minimize the transient, the circuit should be closed at a point on the voltage wave equal to (or later than) the power factor angle. This is called *synchronous switching*. The relation between the supply voltage and the currents obtained by synchronous switching is illustrated by the oscillogram in Fig. 16.32.

Synchronous switching and short accurate welding time are provided by electronic controls and are of greatest importance in welding "stainless" steel and nonferrous metals which must be welded in a very short time — possibly only one cycle of 60 cycle current. A short variation in timing when welding these materials would give a large percentage error in total heating, and would make the welding inconsistent and unreliable, if not impossible.

It was mentioned earlier that the electrodes are made large in cross-section to reduce the generation of heat in them. The current is then localized (current density increased) at the weld section by special forms of electrodes, or by design of the parts. The various methods by which this is done have a characteristic influence on the weld shape, and frequently on the complete design of the parts. In consequence, the

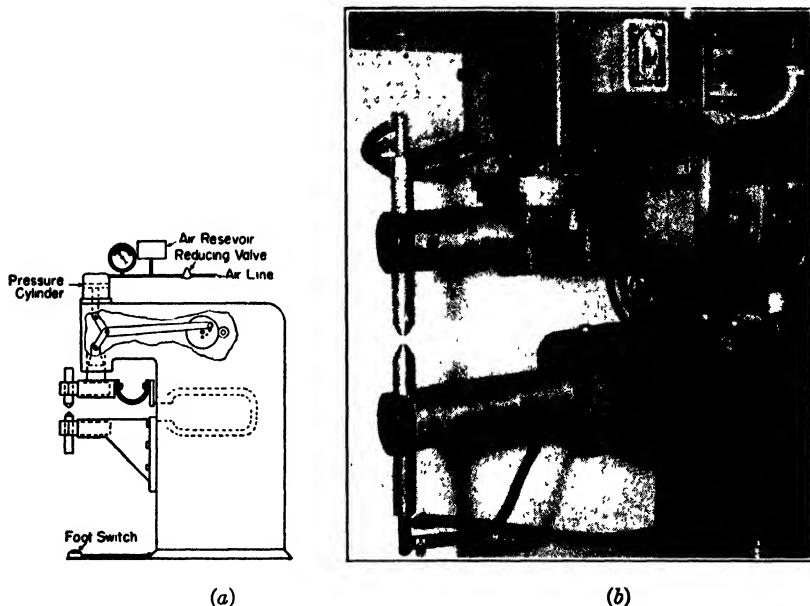


FIG. 16.33. (a) Schematic diagram of a spot welding press.  
 (b) Photograph of water cooled electrodes of spot welder.

resistance welding process is usually referred to by terms which describe the manner of making the weld. The terms in common use are "spot welding," "projection welding," "seam welding," and "butt welding." They are considered distinct types of resistance welding and will be discussed separately.

**16.30. Spot Welding.** In spot welding, electrodes having reduced area at the tips are used for localizing the current and pressure in the parts being joined. The work parts are placed in a machine of the type shown schematically in Fig. 16.33a. After the work is positioned, the foot switch is pressed, initiating the operating cycle of a sequencing control, and in sequence (a) the electrodes are forced against the work by a mechanism such as the toggle linkage and air cushion shown (or by some other mechanical means), (b) the current is turned on and off

by one of the means already described, (c) and after a "push-up" or forging period, (d) the electrodes are raised, and the welded part is removed. The simplicity of the method and the ease with which it may be applied to sheet metal and formed parts of various designs makes it the most widely used form of resistance welding.

*Current and Current Density.* A typical assembly of two workpieces and two electrodes for spot welding is illustrated schematically in Fig. 16.34a. The stock should be wide enough so the weld does not come all the way to the edge, otherwise the metal softened in welding is squeezed out (see Fig. 16.34b), the electrodes or the parts skid, and a weaker weld with poor appearance results. If desired, the extra flange

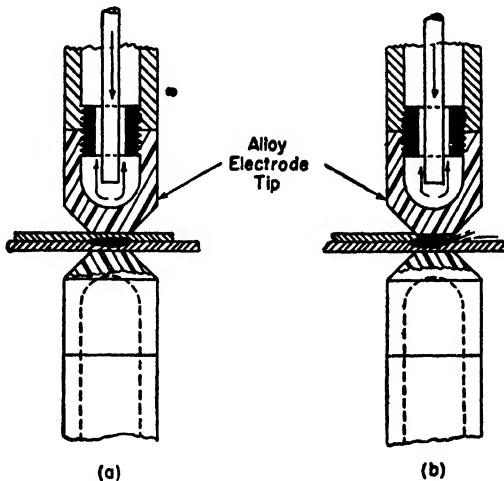


FIG. 16.34. Typical assembly for spot welding showing two workpieces and two electrodes. (a) Correct assembly, soft metal is confined. (b) Wrong, electrode is too near edge of one piece.

width may be trimmed off after welding, but there should be cold metal on all sides of the weld to confine the softened area during the welding process.

The current density throughout the weld area will be reduced by wearing and mushrooming of the electrode points, and if this is allowed to go too far, no weld will be produced. For example, a point  $\frac{1}{4}$  in. in diameter has an area of 0.049 sq in.; if this point is allowed to wear and mushroom to  $\frac{5}{16}$  in. in diameter, or an area of 0.077 sq in., a change of current density of approximately 36 per cent results. Good electrode maintenance is therefore necessary for production of reliable welds.

*Applications.* The spot welding method is used for fabricating all types of sheet metal structures where mechanical strength rather than

water or air tightness is required. Fig. 16.35 illustrates some of the more frequently used types of joints. Such joints may be applied to all types of boxes, cans, enclosing cases, all-metal vacuum tubes, automobile body and chassis construction, light-weight high-speed train construction, freight car building, electric locomotive cabs, panel and other construction on all-metal houses, kitchen utensils, and aircraft.

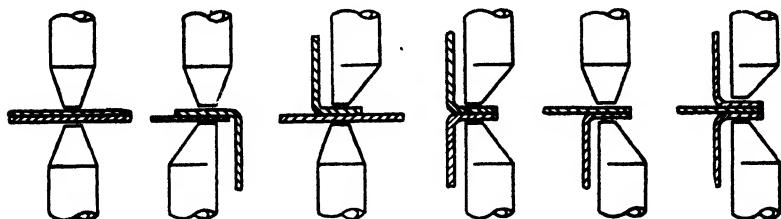


FIG. 16.35. Normal position of spot welded joints to be made with standard electrodes.

Many arrangements other than those shown in Fig. 16.35 are used for applying the electrode to the work. Two of these are shown in Fig. 16.36. The method shown in Fig. 16.36a is one way of making several welds at one time. The separate spot welds must be some distance apart to avoid shunting the current through the work. Fig. 16.36b illustrates a method used for welding without producing surface marking

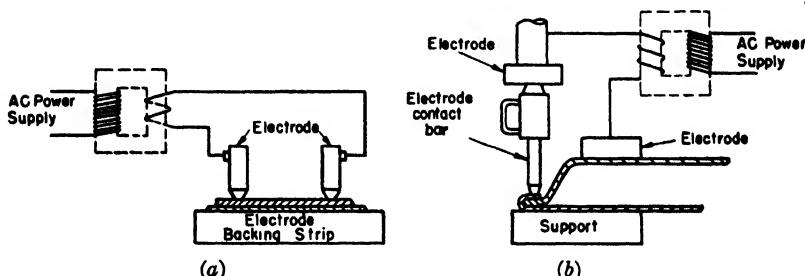


FIG. 16.36. Special methods of spot welding. (a) Multiple welding. (b) Welding without surface marking.

on one side of the weld. When the electrodes are applied to the work as in Fig. 16.34a, there will always be some surface marking owing to heat shrinkage, even if the work surface does not get heated enough to cause discoloration. During heating, the work under the electrode must expand in a horizontal direction, but during cooling the contraction takes place in both the horizontal and the vertical direction, resulting in a ridge a few thousandths of an inch high around the electrode tips,

and a slightly concave work surface under the tips. It is impossible to completely eliminate these marks, but they can be minimized by welding in a short time and by using a much larger electrode on the surface to be unmarked. Another method of getting a smooth surface is to shape the electrode so as to get a slight upset at the weld, and dress this off after welding.

**TABLE 16.6. SIMILAR AND DISSIMILAR METAL COMBINATIONS THAT MAY BE SPOT WELDED**

**Materials.** Practically all combinations of ductile metals and alloys can be spot welded. Some, like copper to aluminum, and aluminum to magnesium, form alloys of practically no strength. Others, such as zinc and some of the high-chromium alloys, experience grain growth even during a very short welding period. Fig. 16.37 shows a photo-micrograph of a satisfactory weld in two pieces of 0.037-in. 18-8 stainless steel sheet. Note that in the very short welding time used the material is affected only part way through the sheet, and the original strength and corrosion resistance of the material are still retained. The short welding period is also necessary in stainless steel to prevent carbide precipitation when the carbon content is high enough to permit it.

High carbon steels weld readily but the weld will be in the full hardened state and will require subsequent heat treatment. This can be accomplished automatically by a control which applies preheating, post-heating, or both as part of the welding cycle.

Zinc-alloy die castings can be welded with little loss of strength, but the ductility is reduced. Free-turning Bessemer screw-machine steel frequently refuses to weld, or results in brittle welds, and hence its use for welded parts should be avoided. Usually, however, when clean,



FIG. 16.37. Photomicrograph of a spot weld in two pieces of 18-8 stainless steel, 0.037 in. thick. Weld made in 1/60 second. Note heat affected zone is approximately halfway through.

properly prepared metal parts are spot welded, the strength of the welds is perfectly satisfactory. Table 16.6 shows combinations which have been successfully welded. Many other combinations may also be satisfactorily welded. Copper and silver are difficult to weld, but they may be welded by the use of low conductivity electrodes (e.g., Elkonite and Trodaloy) already mentioned. In many applications, the weldability of copper is increased if it has a tinned surface.

*Thickness That may be Welded.* Parts of widely different thickness may be spot welded. For example,  $\frac{1}{64}$ -in. material can be welded to a 6-in. piece and would require only slightly more power input and pressure than to weld two pieces of  $\frac{1}{64}$ -in. material, as it is not necessary to heat the 6-in. piece through and the push-up is all obtained on the thinner piece. The limit to welding pieces of equal thickness with an uninterrupted flow of current seems to be approximately  $\frac{1}{8}$  in. Greater thicknesses may be welded by a new technique known as pulsation welding, which will be discussed later.

*Equipment.* Welding equipment of the type shown schematically in Fig. 16.33 is available in many sizes for use on all parts small enough to be brought to the welding machine. For parts which are too bulky or heavy to be readily handled, such as automobile bodies and freight car frames, portable spot welding equipment (called a welding gun, see Fig. 16.38) is available. This equipment has limitations in gage of material that can be welded and has high maintenance costs so that, where possible, the use of the press type of welder is preferred. In

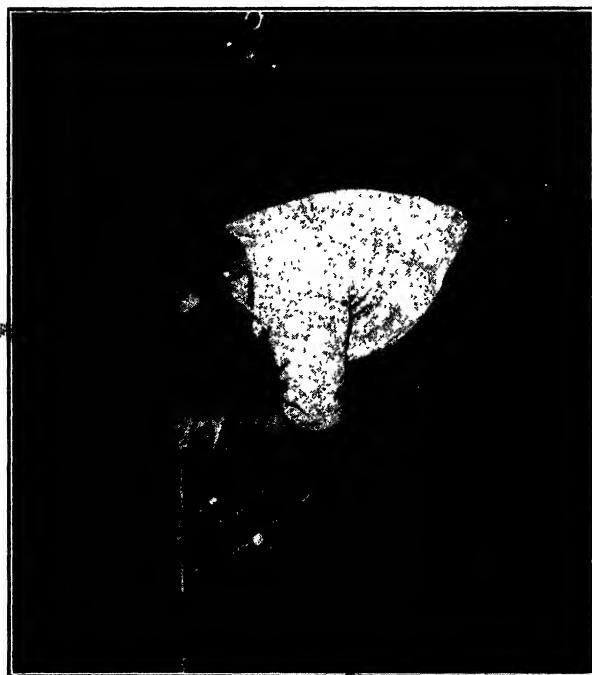


FIG. 16.38. A resistance-welding gun being used for fabricating a switchgear cubicle.

applications where the production justifies the cost, special equipment having multiple electrodes and assembly fixtures can be justified. Many modifications can be built into such machines to speed up their operation and make them largely automatic.

**16.31. Projection Welding.** Projection welding is a modification of spot welding in which the current and pressure are localized at the weld section by the use of embossed, machined, or coined projections on one or both pieces of the work. When the parts can be prepared in this way, the process has the following advantages:

(a) The electrodes are flat, or formed, and contact the parts over considerable area. This results in easier electrode maintenance, more accurate alignment of parts, and simplifies the construction of jigs and fixtures.

(b) By using several projections within the area of the electrodes, several welds may be made simultaneously, thus saving handling time and giving increased output for each machine stroke. It is also possible to make two or more welds closer together than by spot welding as the proximity effect or shunting is eliminated.

(c) Even for a single weld between parts, welding conditions are easily controlled by the use of a projection; the location of the weld, its area, and the surface contact conditions are more certain than when using regular spot welding.

(d) Special parts and assemblies may be welded. For instance, studs with dowel ends are easily assembled to plates; headed pins can be welded through holes in levers, leaving the lever free to move after

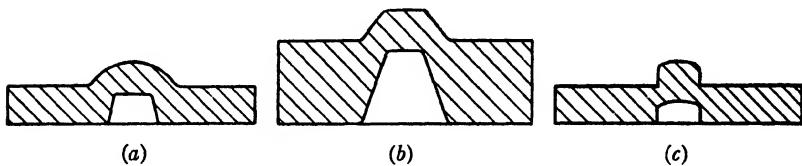


FIG. 16.39. Cross-sections of projections for projection welding. (a) For 24 to 13 gage sheet material. (b) For 12 to 5 gage sheet material. (c) Incorrect type of projection.

fastening; and nonmetallic parts can be fastened onto metal by similar means. It is also frequently possible to make projection welds at sections which are inaccessible to spot welding electrodes.

*Design of Projections, and Applications.* Perhaps the most important step in projection welding is the design of the projections. Practice has indicated that the weld must start with a point or line contact, and have a continuously increasing cross-section. Most of the projection welds made involve the assembly of punched, stamped, or formed parts which permit making the projections as part of the preforming. The projections shown in cross-section in Fig. 16.39 *a* and *b* are suitable for welding most flat or irregular stampings. Oblong, square, oval, and other shapes may be used, but for flat pieces or where the projections contact flat pieces, the round form having a diameter of one or two times the thickness of the sheet gives best results. It also has advantages in simplicity of punch and die design. An elongated projection, Fig. 16.40, is particularly suitable where contact must be made with a

curved surface or at other places where a slight longitudinal or transverse movement may occur. Such a projection assures ample contact surface in the direction of the impending movement. Projections having the cross-section illustrated in Fig. 16.39c should be avoided, since the metal is partially sheared, and the plug may become loose during welding or it may burn off on a line with the upper surface of the sheet.

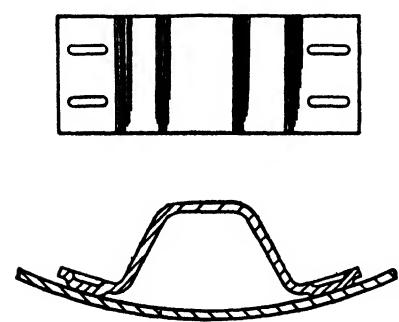


FIG. 16.40. Elongated projections for curved surfaces.

Generally, the projection should be made on the thicker piece when material of different thicknesses is used, and its height should be 10 to 90 per cent of the thickness of the thinner material. The low projections often give satisfactory strength with minimum marking or distortion, and the higher ones give greater strength. If different materials are to be welded, the projections are usually produced on the one with the higher conductivity.

Annular, or ring, projections are often used on screw machine parts such as bosses and studs which are to be welded to sheets up to approximately  $\frac{3}{32}$  in. thick. For thicker sheets, a dome type of projection seems to work out better. Fig. 16.41a shows the correct type of annular projection. When the outside of the part must fit tight against the surface of the sheet, a recess may be left around the projection to provide for the extruded metal. Annular projections are frequently used to provide a pressure tight weld around a hole. The seal weld in all-metal radio tubes is an example of such an application.

Crossed wires as used in most types of wire goods provide ideal projection-welding conditions, and similar conditions can often be obtained when forming parts to be welded. Examples of welds of the cross wire type are refrigerator shelves, baker and butcher baskets, lampshade frames, soap dishes, bird cages, reinforcing mats for concrete roads, and many other similar wire articles of most any combination of wire sizes.

Studs, either plain or threaded, are usually prepared with a spherical dome, using approximately a  $1\frac{1}{2}$ -in. radius on the end to be welded. The round head of a screw without a slot is a very good projection to weld. Special nuts and bolts containing projections are available for

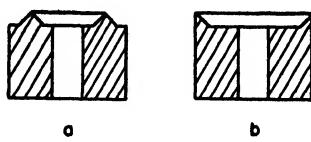


FIG. 16.41. Annular or ring type projections. (a) Correct. (b) Incorrect.

welding to sheets when threaded bosses or threaded through-studs are needed.

In many types of electrical equipment, silver contacts are projection welded to various mountings. These contacts are prepared for welding either by forming a projection directly on the back of the silver or by using steel- or Monel-backed silver contacts, with the backing material formed in a dome. The welding method of attaching contacts is in common use since it saves the silver that would be used in the stems if they were riveted, and the welding operation is less costly than heading over the rivet.

*Material.* Projection welding applies to nearly all the metal combinations that can be spot welded, but the design must be strong enough to support the projection. Combinations of copper and the brasses should be considered difficult to weld on a production basis by this method, and aluminum is not readily welded. It is possible to weld the copper-base metals to steel, however, if the projections are made on the steel part. Coated stock, such as galvanized iron, terneplate, and tin plate, can be welded successfully, but requires special procedure.

*Size and Number of Welds.* The size of projection welds and spot welds is determined by the material, the thickness of the material, and the desired degree of freedom from marking. The number of welds is in turn dependent on the size of the individual welds, the total strength required, and in some instances on the reliability of the manufacturer — sometimes a few extra welds being added for safety. No definite rule can be given for the number or size of welds; each design must be based upon the factors controlling it.

*Welding Time.* When making projection welds, it is very essential to use equipment with sufficient capacity to make the welds in 5 to 30 cycles, particularly when making multiple welds. If this is not done, the projection may not heat evenly enough to develop the full strength of all the welds.

One of the most famous projection-welded products was the Ford wire wheel which was produced for several years. Millions of spokes were projection welded at both ends — to the rim and hub of the wheel without passing through either. There are a great number of other applications, including household refrigerators, distribution transformer tanks, brackets, and lifting hooks. The possibilities seem limited only by the ingenuity of the designer to foresee and make use of the process.

**16.32. Seam Welding.** A seam is a series of overlapping spot welds which, for convenience, are made with two wheels or a wheel and a bar acting as electrodes. The current and pressure are localized at the weld section by reducing the electrode contact area as illustrated in the sche-

matic arrangement in Fig. 16.42. There are many different arrangements of this type of equipment. On some, the work is fed through with driven wheels; on others, the wheels idle and the work is driven by the work table or other separate means.

The normal procedure for making a seam weld is to place the work between the wheels, lower the wheels to contact with the work, and apply pressure. As pressure is applied, the drive is started and the welding current switched on. As the work passes between the welding wheels, an "interrupter" turns on the current long enough to heat the metal to the welding temperature. Then, at the same time the metal is

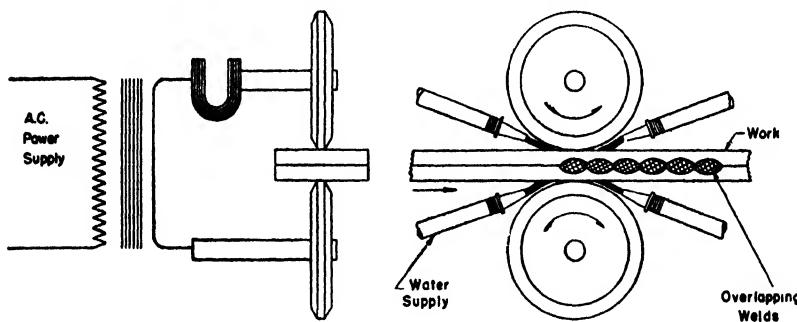


FIG. 16.42. Schematic diagram of welding circuit and arrangement of wheels for seam welding.

pushed together, the current is interrupted so that the weld may chill under pressure and more nearly gain the properties of a spot weld. The interrupter is in continuous operation, and when the current comes on again, the work has traveled a short distance; the welding cycle is then repeated, making another weld which overlaps the first. In this way a pressure-tight seam is made.

The welding is usually done under water to keep the heating of the welding wheels and the work to a minimum, and thus to give lower wheel maintenance and less distortion of the work.

The use of an interrupter helps compensate for differences in surface condition and thickness of material and so prevents burns. Highest welding speed is obtained with electronic interrupting control. It also makes possible more uniform welds because of synchronous switching and absolutely the same "on" and "off" time for each current interruption.

When high work speed and long off-time are used, it is possible to space each weld so it does not overlap the previous one. The result is a sort of "stitch" of spot welds. Where this effect may replace a run

of spot welds, it can usually be done much faster than with standard spot-welding equipment. Typical seam and stitch welds are illustrated in Fig. 16.43.

*Applications.* Seam welding is used on many types of pressure-tight or leakproof tanks for oil switches, transformers, refrigerator evaporators and condensers, automobile gasoline tanks, aircraft tanks, steam radia-

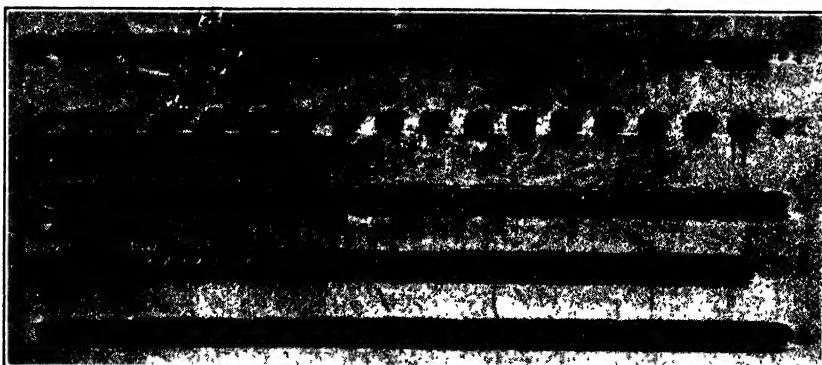


FIG. 16.43. Typical seam and stitch welds. (1) Longer on period than off period. (2)  $1\frac{1}{2}$  spots per inch. (3) 3 spots per inch. (4)  $4\frac{1}{2}$  spots per inch. (5) 6 spots per inch.

tors for house heating purposes, paint and varnish containers, large size metal-shell vacuum tubes, all-metal vacuum bottles or containers used for food and hot drinks, milk handling equipment, and numerous other products.

*Materials and Sizes.* The materials that may be seam welded include most of those that may be spot welded (see Table 16.6). The low carbon steels are perhaps the easiest to weld. Higher carbon steel (0.20 C or more) may be welded but the quenching effect of the adjacent material and the cooling water may require a subsequent heat treatment to give ductility to the weld. The plated steels are welded nearly as easily as the unplated steel, but with both chromium and nickel platings, the appearance is marred and the corrosion resistance reduced at the surface of the weld. The protection of galvanizing, terne, or tin plates is also reduced somewhat, owing to partial pick-up of these platings by the electrode wheels. Copper is almost impossible to seam weld, but most copper alloys and aluminum can be welded at somewhat reduced speed.

Steel plates  $\frac{3}{8}$  in. thick have been seam welded to hold 3000 lb per sq in. pressure. But to date probably half that thickness is the maximum that has been seam welded on a production basis. As in spot

welding, it is possible to weld thin sheet to another part of almost unlimited thickness.

*Design.* The joints and electrode positions for spot welding (see Fig. 16.35) are also used for seam welding. However, the shape of the welding wheels should be considered when checking access of the electrodes to the joint. Worn or mushroomed electrode wheels, like spot welding electrodes, must be replaced frequently to obtain quality production.

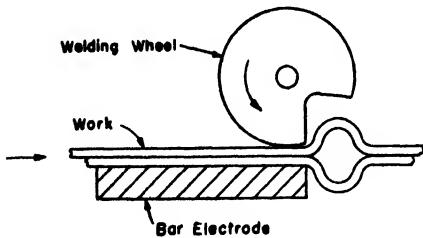


FIG. 16.44. Use of niched welding wheel for seam welding to a header.

In some applications, for instance, refrigerator evaporators, it is desired to weld a seam perpendicular to a large projection or a header. With solid wheel electrodes, this could not be done because of the clearance needed for the wheel, and the remainder of the seam would have to be produced slowly in a regular spot

welder. The use of a welding wheel containing a niche to clear the projection, as illustrated in Fig. 16.44, eliminates this difficulty.

The complexity of seam welding equipment naturally depends on the production and the expected life of the design. Fig. 16.45 shows a four-wheel line welder which was developed for seam welding together two formed halves of a refrigerator condenser. A copper platen is used beneath the work, and the work is fed by a hydraulic table drive. A later design of welding machine had 10 welding wheels and could complete all 20 of the 4-ft seam welds on the condenser in two passes — indexing between.

**16.33. Butt Welding.** There are two types of butt welding — upset and flash.

*Upset Butt Welding.* In a weld of this type the parts to be welded are clamped edge to edge in the welding machine in the proper alignment, and with the proper amount of pressure. The current is turned on and the part is heated by its resistance (particularly its contact resistance) until the welding temperature is reached. At this point, the pressure applied upsets or forges the parts together. The pressure may be applied manually by a lever or toggle, or it may be applied hydraulically or through a spring. The kind of material and the size of parts determine the method to be used. Materials with a very short plastic range, like copper or aluminum, usually weld best with a spring push-up machine, since with these materials the push-up point is limited to a narrow pressure range. If this range is exceeded, the metal melts

and slumps off instead of welding. The quick acting spring will always follow the metal as fast as it upsets, preventing the slumping or "burning off" action.

Upset butt welding is used principally on nonferrous materials for welding bars, rods, wire, tubing, formed parts, etc. The electrodes are made in the form of grips or jaws and must cover a large enough area

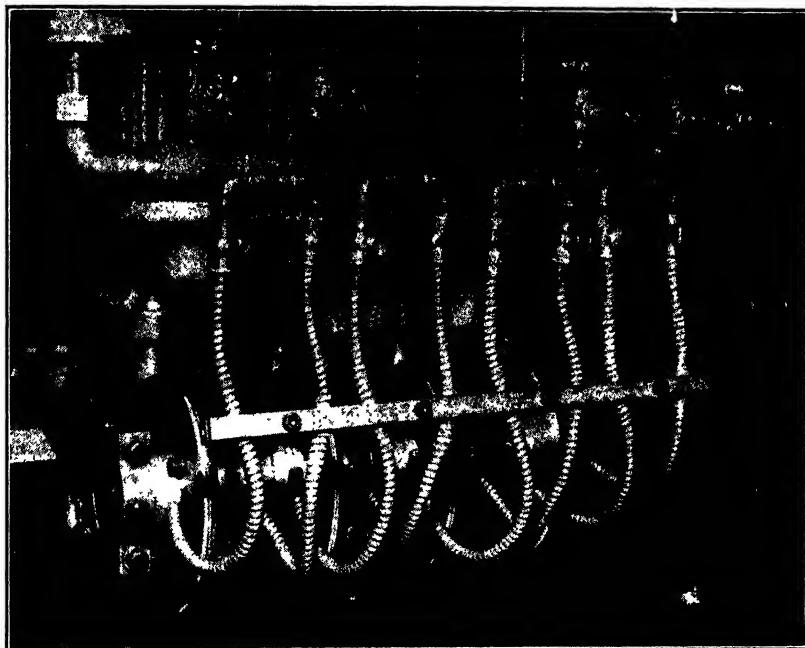


FIG. 16.45. Welding parallel seams in refrigerating machine condenser plates with welder having four wheels.

to hold the parts true and to introduce the high current into the parts uniformly without creating hot spots. Typical applications include (a) welding lengths of wire together in the wire mill for making continuous wires for drawing, (b) butt welding copper end rings for squirrel cage rotors for induction motors, (c) making aluminum wire gaskets for mercury arc rectifiers, and (d) for welding lead-in wires for incandescent lamps and vacuum tubes.

An interesting upset butt welding application has been developed recently for welding copper to aluminum. It was found desirable to use some current carrying coils of aluminum to obtain low weight and inertia. At both ends of the coil a section of copper had to be welded to the aluminum for terminal connections, since the mechanical connec-

tion of aluminum to other materials is not always satisfactory because of the high resistance of the oxidized aluminum surface. In making the copper-aluminum weld, a low pressure was used during the heating period, then much higher pressure was applied during the push-up period to squeeze out the brittle eutectic alloy formed in the joint. The results were satisfactory from the standpoint of both strength and corrosion resistance.

*Flash Butt Welding.* Flash butt welding is the most widely used butt welding method. In this process the parts to be welded are clamped to the electrode fixtures, as in upset butt welding, but the voltage is applied before the parts are butted together. As the parts touch each other, an arc is established which continues as long as the parts advance at the correct speed. This arc burns away a portion of the material from each piece. When the welding temperature is reached, the speed of travel is increased, the power switched off, and the weld is upset.

Of all the welding processes described, flash butt welding is the only one in which nearly all the heat in the weld does not come from the resistance of the weld parts to the welding current. The arc drawn between the work parts supplies practically all the heat, although some is produced by resistance and some by combustion of the work surfaces. Flash butt welding has displaced the upset method of welding most materials for the following reasons:

- (1) Less power is consumed because the arc creates more heat with a given current.
- (2) The joining surfaces need no particular preparation but are burned to a fit.
- (3) Since the surfaces are burned away, the weld is made in clean virgin metal.
- (4) The upset is smaller, so there is less material on the surface of the finished part to mar the appearance.

When appearance of the work is important, both flash spatter and irregular extrusion must be dressed off. A good many different materials and combinations can be flash butt welded; steels and the ferrous alloys other than cast iron are probably the most easily welded. Those materials which cannot be flash butt welded are lead, tin, zinc, antimony, bismuth and their alloys, and the copper alloys in which these metals are present in large percentages. Combinations of these materials are butt welded by the upset method.

In the design of parts to be flash butt welded, an allowance in length of the individual parts must be included when it is necessary to control the over-all length. This allowance provides the metal to be burned off and also the metal for filling recesses and for extrusion at the surface

during push-up. Allowances may vary from one to six times the material thickness, but on the average the allowances given in Fig. 16.46 are satisfactory for hydraulic or cam operated welders. For manual welders, the allowances given may be reduced to 25 to 50 per cent.

The flash butt welding process is used extensively in automobile construction, on the body, axles, wheels, frame, and other parts. Other applications include welding motor frames, transformer tanks, and many types of sheet steel containers such as oil barrels and floats, and for welding shanks of mild steel to tools of high-speed steel, such as drills and reamers.

It should also be noted that in both methods of butt welding, the electrodes which apply the forging pressure are often somewhat removed from the weld section. Since the pressure must therefore be transferred through the work, the designer should provide sufficient strength and stiffness in the supporting members.

**16.34. Special Welding Equipment.** In Sec. 16.29 it was mentioned that the usual source of electrical power for the various methods of resistance welding is a welding transformer which has either primary taps or an electronic circuit to provide heat control. Three other types of power supply are used to some extent and will be described briefly.

*Pulsation Welding.* In this method of welding, the electronic current interrupter used for seam welding is, in effect, applied to spot, projection, and butt welding. The weld is made by interrupting the current one or more times without release of pressure or change in location of the electrodes. There are two main reasons for interrupting the current in this way. First, it is possible to get better heat distribution in the weld section, and second, the water cooling of the electrodes is made more effective.

Better heat distribution in the weld section is particularly important when welding multiple projections or large annular projections in heavy gage materials where a lot of heat is needed. If this heat is applied with low current for a long period, poor distribution of heat usually results and some of the projections may not weld. The pulsation

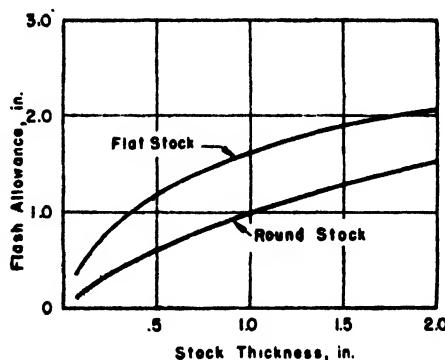


FIG. 16.46. Average allowances for flash butt welding with machine operated equipment.

method uses a larger current which forces better distribution, but the current is interrupted before any molten metal can be squirted out of the joint. During the "off" time, the heat spreads. The next impulse of current applied raises the temperature a little higher, and further impulses are applied until all projections or the entire annular projection reaches the welding temperature.

Improvement of electrode cooling is important in spot welding thick sections or materials of low conductivity. For instance, if two pieces of 1-in. material were to be welded with an uninterrupted current flow, the electrodes would undoubtedly heat to their softening point before the work reached the welding temperature. The use of pulsation welding permits the water cooling to lower the temperature of the electrodes enough during the "off" period so they will not overheat while the current is on. The work, on the other hand, is thick enough or of low enough conductivity so the cooling of the electrodes will only slightly affect the temperature at the weld section. The use of pulsation welding with a spot welding machine capable of exerting heavy pressure has made possible spot welding of combinations like two pieces of 1-in. material; or a piece  $1\frac{1}{2}$  in. thick between two 1 in. pieces, or a  $\frac{1}{2}$  in. piece to a piece of any thickness up to 4 in. At present the pulsation method is used for spot welding most work (two pieces)  $\frac{3}{2}$  in. or thicker. As many as several hundred welds may be made without changing or redressing electrodes. Other advantages of the method are reduced distortion, and maintenance of material properties such as corrosion resistance at the surface of the part.

*Percussion Welding.* Percussion welding is a form of flash butt welding. In place of the welding transformer, a capacitor is used for the power supply. Energy is stored in the capacitor, and when the weld is to be made, the two parts are rapidly propelled toward each other. Just before contact between the parts is established, the electrical energy in the capacitor is discharged, creating an arc between the parts and melting their surfaces. The impact provides the forging action. The very short duration of current flow makes the conductivity of the material being welded and its melting temperature of little importance and permits the welding of very dissimilar materials, e.g., stainless steel to aluminum. The short arc time also confines fusion to the metal surfaces and results in almost complete absence of flash.

There are several limitations to the process. The parts must be separate and the weld is limited to  $\frac{1}{2}$  sq in. This limitation is caused by the need for excessive safety precautions (the voltages for work of this size are quite high, possibly 7000 volts) and by the difficulty of controlling the current. Actually the process is usually used on much

smaller work, e.g., wires up to 0.010 to 0.030 in. diameter, because of the large size of capacitors needed for heavy work.

*Stored Energy Welding.* This type of welding involves storing the energy for producing the weld in a suitable reservoir, usually at a slow rate, and then delivering it to the weld, usually at a comparatively high rate. Strictly speaking, percussion welding uses a power supply of this type, but the term "stored energy welding" is more commonly associated with the spot or projection welding process.

Two methods for storing electrical energy are used. One is the electrostatic type in which a bank of capacitors is charged by a three-phase rectifier. When the proper value of charge is reached, a contactor is closed, and the capacitors are discharged into the primary of a specially designed transformer. The sudden current flow induces a voltage in the secondary of the transformer which causes an impulse of welding current. This impulse of welding current reaches its maximum value very quickly, then gradually drops to zero.

The second method operates on the electromagnetic principle. A three-phase rectifier is again used, but the energy is stored magnetically in a special transformer. Upon interrupting the direct current flow, the field sustained by that current collapses, and the energy stored in the field is transmitted to the secondary winding where it is dissipated in a high surge of current through the secondary circuit.

The electrostatic method has the advantage of higher operating speed and control of wave shape. The main advantages of the electromagnetic method are simplicity and compactness, the wave shape and maximum current being fixed by the design. The advantages of both methods over a regular a-c supply are as follows:

- (1) The balanced three-phase load on the line eliminates high-current single-phase loads.
- (2) Lower current is taken from the line, since a considerable length of time can be used to store the energy. This reduces the (peak) power required.
- (3) Metal pick-up by the electrodes is reduced, so the electrode life is increased.

This equipment has been found of especial value in welding aircraft structures of aluminum and for welding other nonferrous metals.

**16.35. Uses for Resistance Welding Equipment, Other than Welding.** Resistance welding equipment has many miscellaneous uses that cannot be classified as welding. Several of these are mentioned below.

*Burning Holes in Hardened Parts.* By using a tungsten punch and a copper die as spot welding electrodes, holes can be burned in hardened steel parts such as saws, thin milling cutters, and flat spring stock.

The holes are clean, they do not start cracks in the adjacent material, and the annealing action does not extend any appreciable distance from the hole. The method is fast — a hole can be burned in  $\frac{1}{32}$ -in. stock in a quarter of a second. Although these holes are not as accurate as drilled holes, they are satisfactory for many purposes. .

**Annealing.** Both spot welders and butt welders have been used for annealing. With the latter, such parts as tubing, wire, structural shapes, and hardened shafts that are to be straightened have been annealed, and pipe angles and many other parts have been heated prior to bending. This method is quicker than a torch or furnace and much cheaper.

**Brazing and Soldering.** A number of the brazing and soldering processes discussed in the previous section make use of resistance heating. Advantages gained are lower operating cost, less work distortion, and increased cleanliness. Machines of the spot welder type are most frequently used, but portable tongs with carbon electrodes are also available for brazing electrical connections in transformers, motors, generators, and other types of electrical equipment.

**16.36. Design of Parts for Resistance Welding.** In addition to the points mentioned in connection with the discussion of each of the methods of welding, the following should be borne in mind when designing parts for resistance welding.

**General Considerations.** Simplicity should be given first consideration. As the product is designed, its features should be chosen to take full advantage of the weld method to be used. A particular check should be made to assure accessibility of the electrodes to the parts, and, where possible, welding of the entire assembly with one setup should be considered because of the extra cost involved in setting up the machine in a different manner several times during the welding of one assembly.

The practice of making hand-made full-scale samples, or small-scale models to determine the accessibility of the various parts of the equipment available will many times furnish suggestions of minor changes in the design which make the welding easier and will greatly reduce the cost of welding. Full-scale samples may also be used to determine the type and capacity of welding equipment to use for the job.

When considering a change from another method of fabrication to resistance welding, the designer should study the product from the welding viewpoint. Frequently it is possible to reduce the material used by taking advantage of the strength of a joint when it is welded instead of being weakened by holes for riveting, bolting, etc. Other savings may be gained (*a*) by changing from a lock seam to a butt or

seam weld, (b) where welding avoids the waste of material in some types of bayonets or tongues and slot joints, and the cost of complicated dies for making these, and (c) from the possibility of welding several thicknesses of material together at one time or from joining a thick and a thin piece at some section.

The quality and accuracy of a resistance welded assembly are determined by the equipment used and by the way in which the jigs, tools, fixtures, and machines are set up and maintained. Preparation of parts for welding by any method should be done carefully so that the component parts of an assembly will fit together without requiring the operator to spend time straightening or hand-fitting them. It is emphasized that the accuracy of a welded assembly can be no better than its component parts. The various types of welders cannot be expected to act as hydraulic presses to correct improperly formed fits. The copper alloy dies, electrodes, and fixtures will not hold up under the forming work, and the pressure at the weld junction will differ from part to part.

*Materials.* The various materials that can be welded have already been discussed at some length (see Table 16.6). Note that the welding of high carbon steel will result in brittleness in the heat affected zone. Such welds are very likely to fail in vibration or shock and are not reliable unless the weld area or the entire part can be heat treated. Sometimes this may be done by a post cycle of reduced current on the welding machine. The precipitation hardened aluminum alloys are also affected by the welding heat and may require some heat treatment after welding to restore properties.

*Preparation of Material.* Cleaning metal in preparation for welding is one of the most important factors in controlling the quality and consistency of the product. Unfortunately, it is the one factor that is most frequently neglected. As has been pointed out, the resistance of the contact surfaces is very important when making welds. If various thicknesses of scale, grease, dirt, paint, oxide, and rust are on the material, the contact resistance cannot be expected to be uniform on all parts. The differences in heating which result will certainly make welding inconsistent, if any weld is made at all, and they introduce the possibility of gas inclusions or slag inclusions in the fused metal. Scale also causes excessive burning and marking of the metal surface and the electrodes.

Blasting with sharp steel grit is frequently recommended as a method of cleaning material for welding. The use of shot should be discouraged, as particles of scale are driven into the surface and the contact resistance becomes quite variable. Tumbling in a tumbling barrel will burnish the surface of parts but will not remove scale. Sand blasting must not

be used on any material for resistance welding because enough sand may be driven into the surface of the parts to actually insulate them from each other, or at least to cause a great variation in contact resistance.

Successful cleaning has been done by many methods such as pickling, grinding, steel grit blasting, and scrubbing (of soft materials) with steel wool. When pickling, a bright pickle is preferable. Rinsing



FIG. 16.47. Distribution transformer tank completely fabricated with resistance welding.

should be thorough to remove any residue left on the material from the pickling solution, and the cleaning should be done shortly before the material is used.

*Weld Strength.* There are very few design data available on the strength to be expected from the various types of welds. Perhaps the best method of assuring adequate strength is to make sample welds in the material to be used, and test these to destruction. The effect of both number and location of welds can be checked in this way. Seam welds may be tested by welding completely around two pieces, welding

a nipple to one, and expanding the test assembly by pumping water through the nipple. Simple tensile tests usually suffice for butt welds, and both shear and tensile tests may be employed for spot and seam welds. Fatigue tests are quite important for applications involving cyclic loads since stress raisers of various types may be introduced by the welding.

Several other considerations which are of importance in certain designs for resistance welding are as follows:

(1) The position of the electrodes should be such that a minimum amount of magnetic material is introduced into the secondary loop of the welding transformer. Magnetic material in this loop will absorb a great deal of power, so the bulk of the workpieces should be kept on the outside. Considerable power will also be absorbed when the part loops the electrode for any distance because this is favorable to establishing eddy currents of large magnitude.

(2) One workpiece may be located with respect to another by a plug, if the plug does not shunt too much current from the weld section.

(3) Spot welding can frequently be used to advantage as a means of fastening two workpieces to assure positioning for some subsequent operation such as brazing or seam welding.

(4) The possibilities of resistance welding can often be extended by using combinations of the various welding processes, and by welding subassemblies which are later assembled and welded to form the completed article. (See Fig. 16.47.)

**16.37. Conclusion.** In conclusion, it is emphasized that the welds produced by any resistance welding methods will be just as consistent in quality and appearance as the product manufactured by any other method of fabrication if the same care is taken in the selection of equipment, supervision and training of operators, and selection and preparation of material. The cost of fabricating by welding frequently shows a large saving over riveting, brazing, soldering, or other methods used, particularly when the production is large. Many times these savings are as much as 50 to 75 per cent. However, low cost welding requires suitable design of parts to employ the advantages offered by the processes.

#### NONPRESSURE WELDING

By R. M. Rood and J. F. YOUNG

**16.38. General.** Nonpressure welding is defined as the intimate joining of metals by the application of heat without the use of pressure. The process consists in applying intense heat to the surfaces being joined

such that local fusion of these surfaces and admixture of the molten metals takes place. Filler metal of composition similar to the metals being welded may be melted into the joint when necessary. On cooling and solidifying, the weld metal assumes a fine grain cast structure which may have properties very nearly equal to those of the base metals.

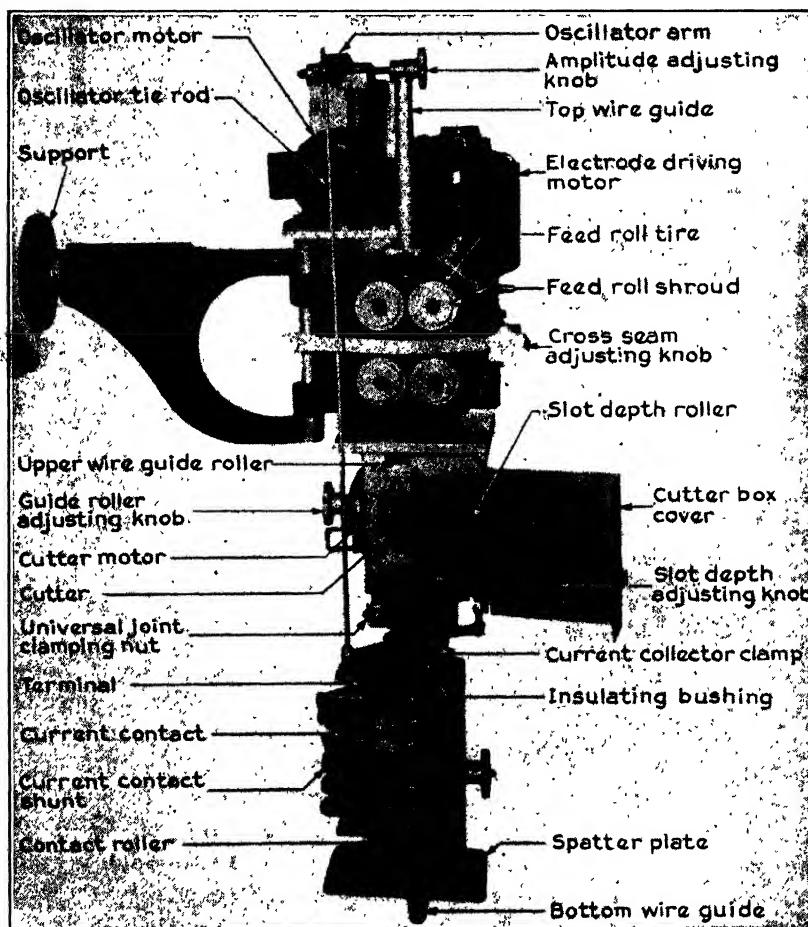


FIG. 16.48a. Automatic arc welding head for use with heavily coated electrode.

Weld metal is now recognized as an engineering material having reliable physical properties, and many types of structures when properly designed for nonpressure welding can be fabricated economically by this process.

This type of welding is widely used in fabrication and repair work on

building and machine structures, transportation vehicles, containers, and numerous other metal products. It is also used in the repair of defective castings and in the correction of machining errors, and to produce hard surfaces to resist wear and abrasion.

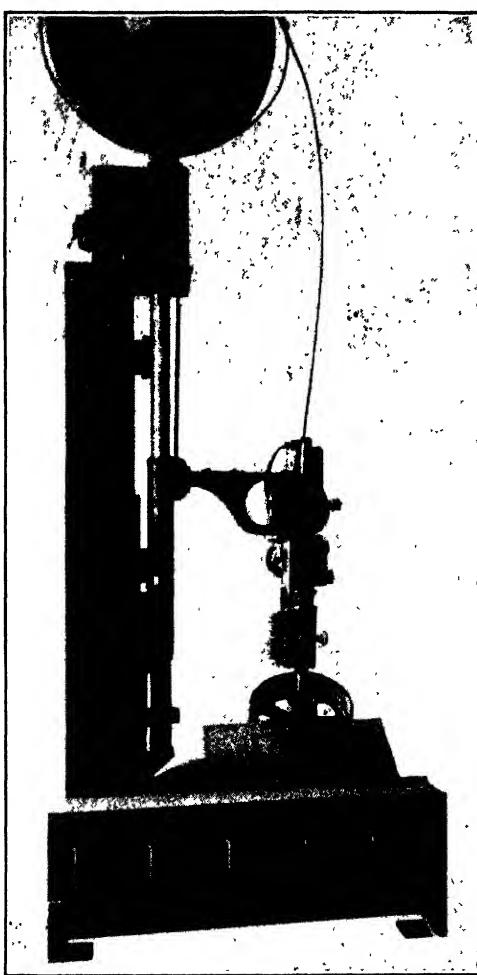


FIG. 16.48b. Application of automatic arc welding head on a circular seam welder for arc welding 16-in. diameter tank wheels (shown in position for making hub weld).

Designs utilizing nonpressure welding often have advantages of increased strength, compactness, reduced weight, and reduced cost compared with designs for other methods of manufacturing. For small parts

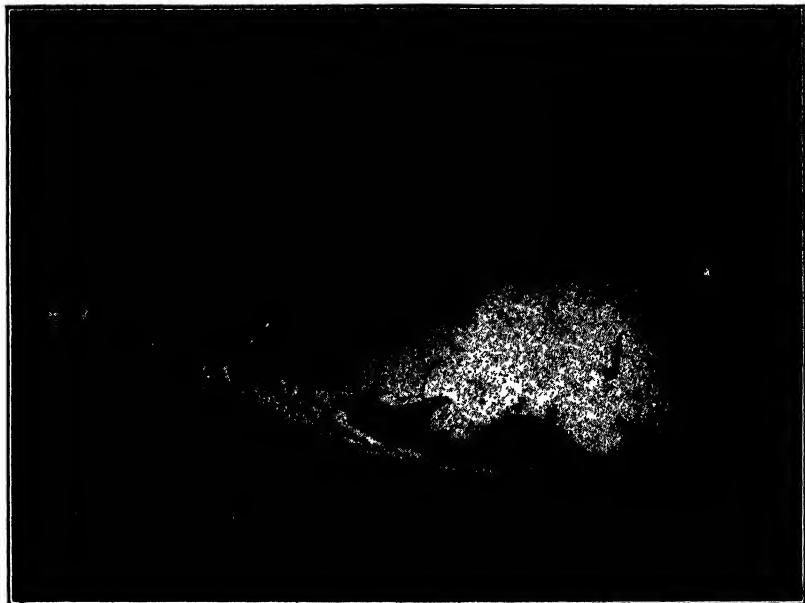
in large numbers, however, casting or forging may be more economical, or fabrication by a pressure welding process may be more suitable than nonpressure welding.

In order to properly design for nonpressure welding, the engineer should know what processes are available for this kind of welding and the types of work that can be accomplished with each process. He must also understand the characteristic effects of these processes on the parts being welded. In this section various processes are described, together with those characteristics which have an influence on product design.

**16.39. Processes.** The processes utilized for nonpressure welding are outlined in the Master Chart of Welding Processes (Fig. 16.1). It will be seen that there are three sources of heat: the electric arc, the gas flame, and the Thermit reaction. Each of the numerous processes utilizing these sources of heat finds special application, depending on the materials being welded, the size and type of joint to be made, and other factors governing the economics of the job. Frequently several processes may be used to produce welds of equally high quality, and a choice of process is then made on the basis of its availability and operating cost. Any of these processes, with the possible exception of Thermit welding, may be adapted to automatic operation (Fig. 16.48). For heavy structures of ferrous materials, the metal arc process has achieved widest use because of the speed and ease of welding.

**16.40. Metal Arc Process.** In the metal arc process the heat is obtained from an arc formed between the work and a metal electrode, which also supplies molten filler metal to the joint. In operation, the intense heat of the arc forms a molten pool in the metal being welded and at the same time melts the tip of the electrode. As the arc is maintained, molten filler metal from the electrode tip is transferred across the arc, where it fuses with the molten base metal, as shown by Fig. 16.49.

Both alternating and direct current are used for metal arc welding. With direct current a variation in arcing characteristics is obtained by changing the electrode polarity, and this fact has facilitated the development of electrodes. A great disadvantage of d-c welding, however, is the presence of arc-blow under certain welding conditions. Arc-blow is the distortion of the arc stream from the intended path owing to magnetic forces of a nonuniform magnetic field. It is especially noticeable when welding in a corner or at the end of a groove. Arc-blow makes welding difficult and definitely limits the amount of current and size of electrode which can be used. With alternating current arc-blow is greatly reduced and higher currents with larger electrodes may be used to increase the rate of weld production and reduce costs.



(a)



(b)

FIG. 16.49. (a) Artist's drawing of metal arc showing weld metal piling up to form a bead, and the formation of a slag coating.  
(b) Actual photograph of metal arc.

Highest quality weld metal is produced when the conditions of melting conform to the best electric-furnace steel melting practice. These conditions are the protection of the molten metal from the oxygen and nitrogen of the air, and the use of fluxing and slagging ingredients to remove impurities. To produce these conditions in metal arc welding, the electrode is coated with a heavy covering of flux which produces in the arc either a shield of nonoxidizing gas or a molten slag cover for the weld metal, or both. Besides these duties, the coating produces

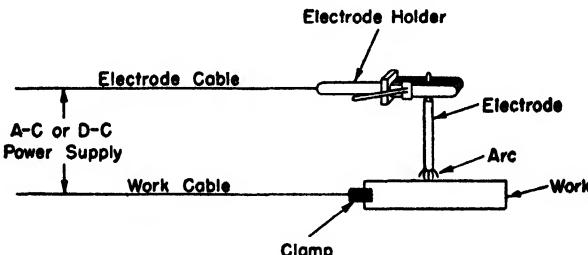


FIG. 16.50. Elementary diagram of circuit components for metal arc welding. The power may be supplied by an a-c "stepdown" transformer, a d-c welding generator, or a d-c constant-potential generator and resistors.

ionized vapors to stabilize the arc and governs the melting rate and amount of penetration into the parts being welded. The coating also sometimes serves to introduce certain alloying elements to the weld metal. Shielded arc electrodes produce a quality of weld metal superior to that produced by bare electrodes and lightly coated electrodes; therefore use of the latter has been superseded in many applications by heavily coated electrodes.

Besides the use of coated electrodes, the shielding action of a coating may be achieved in automatic welding by using a bare electrode and submerging the arc and melt in a powdered flux. This process, known as submerged melt welding, is a machine welding process used on large production work in the flat position. Extremely high currents are used and heavy welds are often made in a single pass. The quality of the weld is in most ways comparable to that of manual welding with heavy coated electrodes.

The metal arc process differs from most other nonpressure processes in that the application of filler metal is simultaneous with the application of heat, and control over the temperature and flow of molten metal is not as readily obtained as with the processes where the addition of filler metal is under separate control. This characteristic of the process

limits its use on very fine work. The highly concentrated heat of the arc makes this process superior to others from the standpoint of controlling distortion.

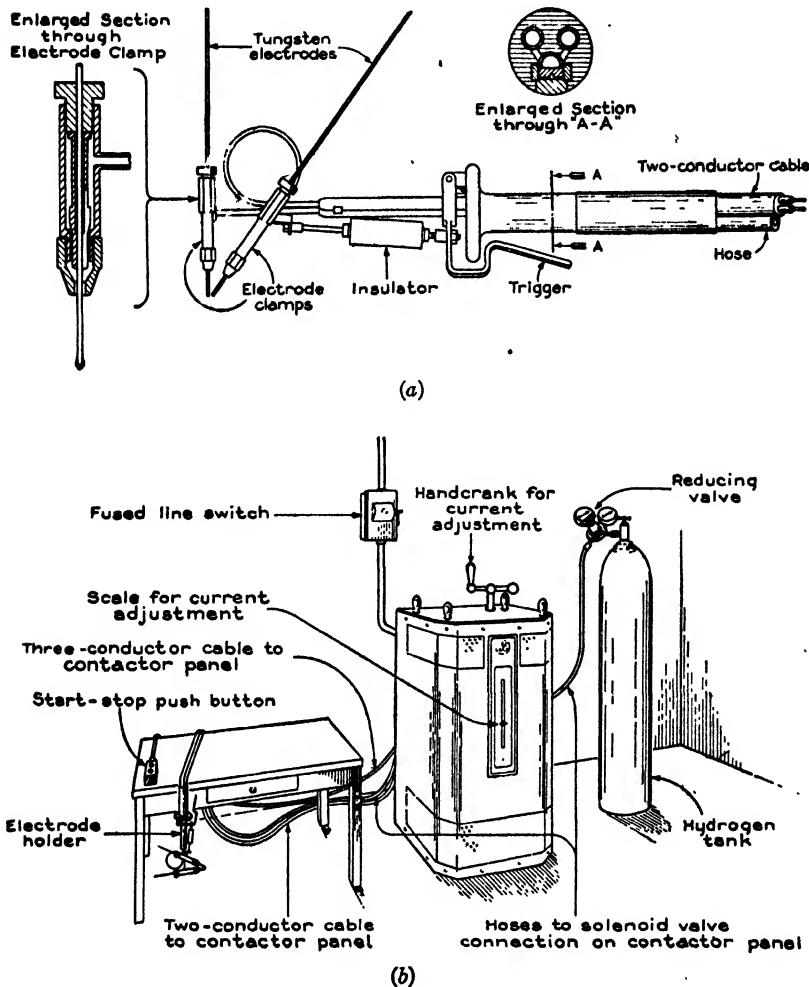


FIG. 16.51. (a) Side elevation of an electrode holder for atomic hydrogen arc welding.  
 (b) Sketch of equipment set up for atomic hydrogen arc welding.

Metals most suited to welding by the metal arc process are low carbon steels and the high alloy austenitic stainless steels. With other steels such as low and medium alloy steels many precautions must be taken

to produce ductile joints, and welding of these materials is not recommended where it can be avoided. Of the nonferrous materials, aluminum alloys, and nickel alloys are sometimes welded by this process with the use of suitable heavy-coated nonferrous electrodes.

**16.41. Atomic Hydrogen Arc Welding Process.** In atomic hydrogen welding, the heat is obtained from an a-c arc drawn between two tungsten electrodes in an atmosphere of hydrogen (see Fig. 16.51). Alternating current is employed so the two electrodes will be consumed uniformly. These electrodes do not enter into the weld metal, and if a filler is needed it must be fed into the arc separately.

The heat of the arc is transferred to the work largely by means of dissociation and recombination of molecular hydrogen. The molecular hydrogen supplied through the electrode holder is dissociated to atomic hydrogen in the arc and recombines on contact with the cooler base metal, giving up heat energy at a very high temperature. Heat control is had by varying the length of arc between electrodes and by varying the distance between the arc stream and the work. The envelope of hydrogen gas also supplies a reducing atmosphere and shields the molten metal from oxygen and nitrogen.

The atomic hydrogen process is especially adapted to repair welding of metal molds and dies made of alloy steel because welds of exactly the same chemical analysis as the base metal can be made, thus making possible a uniform structure through heat treatment. Welds are homogeneous and smooth in appearance, because the hydrogen keeps the molten metal clean and the arc causes no turbulence in the molten pool. Atomic hydrogen arc welding is also used with outstanding success in welding thin materials including carbon steel, stainless steel, aluminum, and Monel metal.

**16.42. Helium Shielded Arc Process.** The helium shielded arc process is now used primarily for the welding of magnesium alloys. In this process the heat is developed by a d-c arc drawn between the work and a tungsten or carbon electrode in a shielding atmosphere of helium. Filler metal when required is added in rod form. This process may have important applications to the arc welding of thin ferrous sheet materials as well as to magnesium and other nonferrous alloys.

**16.43. Carbon Arc Process.** In carbon arc welding, a carbon or graphite electrode is used and the filler metal, if required, is added separately in rod form. Direct current is used. Shields, either gas or flux, may or may not be used, their function being the same as in the metal arc.

This type of welding is not widely used. It finds some special application in the welding of copper and its alloys.

**16.44. Gas Welding Process.** In gas welding, the welding heat is furnished by a flame resulting from the combination of a fuel gas such as acetylene or hydrogen with oxygen; oxyacetylene, being capable of producing the highest temperature flame, is the most used. Heat is controlled by varying the tip sizes and gas pressures and also by the position of the torch.

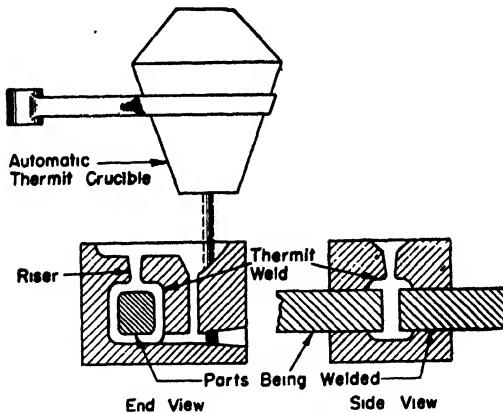


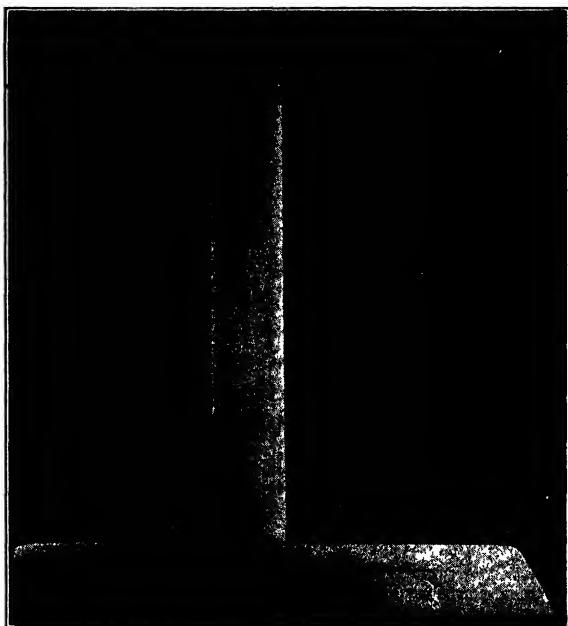
FIG. 16.52. Sketch of a crucible and mold for Thermit welding.

The filler metal, when required, is added separately in rod form, and fluxes in powder or paste form are applied either to the work or to the filler metal.

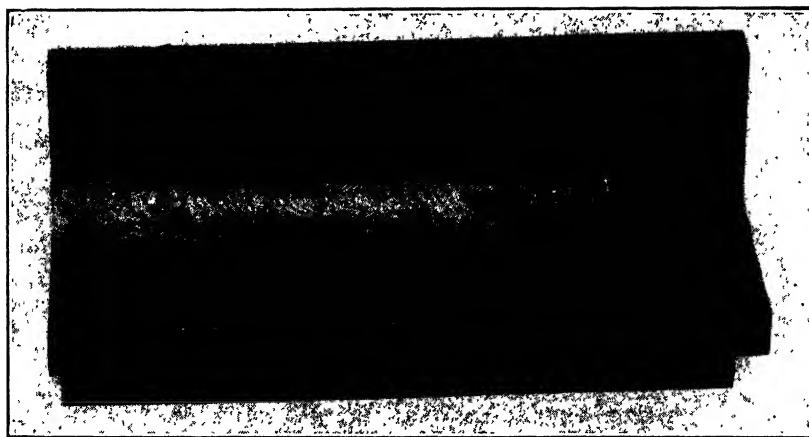
One advantage of these processes is that the gas torch may be adjusted to produce a reducing, neutral, or oxidizing flame. The oxyacetylene flame makes it possible, if desired, to control to some degree the carbon content of the deposited steel weld metal.

Another advantage of gas welding is that the equipment used is more portable than that for the arc process. Gas welding can be applied to welding practically all ferrous and nonferrous metal parts, and is used extensively for repairing gray cast iron parts and welding small diameter piping and tubing (2 in. diameter and under). It may also be used in depositing surfacing materials.

**16.45. Thermit Welding Process.** In nonpressure Thermit welding, liquid steel produced by the Thermit reaction flows into a mold surrounding the parts to be joined and furnishes both the welding heat and the filler metal. (See Fig. 16.52.) The Thermit reaction, which is produced by igniting a mixture of finely divided aluminum and iron oxide, yields a highly superheated molten iron and slag of aluminum oxide. Suitable alloying elements are added to the mixture to produce



(a)



(b)

FIG. 16.53. A single pass fillet correctly arc welded in the flat position with  $\frac{1}{4}$  in. diameter electrode.

- (a) Macrosection showing flat contour, good fusion, and heat affected zone.
- (b) View showing smooth appearance obtained with correct technique.

steel of the desired composition. Metallurgically, these welds are very sound and strong, and they may be made with a minimum of distortion and residual stress because of the rapidity with which the welding is done, and the slowness of cooling. The process is limited to heavy joints of near-square proportions and is used principally for heavy repair work. It has important applications in the shipping, steel, and railroad industries.

**16.46. Effects of Welding Heat.** There are certain effects common to all the nonpressure welding processes which the designer must appreciate in order to design a product so that it may be suitable to welding. These are the metallurgical and mechanical effects of welding heat on the parts being welded. The region of the base metal which has undergone a metallurgical change as a result of the exposure to the welding heat is called the *heat affected zone* (see Fig. 16.53). The metal in this zone has been heated and cooled through a range of temperature great enough to cause physical changes in the structure of the metal with consequent changes in physical properties. The amount of change may be controlled to some extent by the use of suitable welding procedures, and sometimes the original properties may be restored by heat treatment after welding.

With steels, a hard zone will be produced depending on the degree to which the particular steel is air hardening. Accompanying the hardening will be a loss of ductility which will decrease the resistance to shock or fatigue. Brittleness may also exist through the development of a coarse grain structure. Any metal, the properties of which are attained by cold working or heat treating, will have an annealed and softened zone adjacent to the weld. Certain stainless alloys will have their corrosion resistance greatly reduced by carbide precipitation in the heat affected zone. All of these effects must be appreciated if improper applications of welding are to be avoided. The mechanical strength of weld metals is at least equal to that of the base metals, but the presence of the metallurgical changes mentioned can greatly reduce the strength and associated properties of the joint, particularly for fatigue and shock.

The mechanical effects of welding heat are the distortion and residual stress resulting from welding. The magnitude of these effects will depend on factors of design and welding procedure, but the effects will always be present to a certain extent in any structure fabricated or repaired by nonpressure welding. Distortion and residual stress result from the expansions and contractions which accompany the temperature changes during the process of welding. The base metal heated locally will expand and upset owing to the restraint imposed by the surrounding colder metal. On cooling, this upset portion of the base metal will

contract beyond its original dimensions and thereby set up internal stresses causing distortion. If the parts being welded are not free to move, high residual stresses will be formed which may often reduce the load carrying ability of the structure or even cause cracking during welding. The best method of assuring low residual stresses is to design the parts so they will have as little resistance as possible to the weld contraction during cooling.

When it is not possible to avoid high residual stresses, they may be relieved by a stress relief heat treatment, or by hammering (peening) to cause local yielding. This latter practice, however, is not generally recommended owing to the inconsistent results of various operators. Preheating the whole structure may likewise prove helpful as a means of reducing residual stress. Other shop procedures and a proper welding sequence are also of importance in limiting the distortion and internal stress, although the latter cannot be avoided entirely.

**16.47. Weldability.** There are probably no materials which cannot be welded by some fusion process if sufficient control is exercised over all metallurgical factors. It is seldom practical, however, to employ materials in a welded design which require special treatment and complicated welding procedures. The engineer designing for welded construction must consider the weldability of materials and must decide not whether a material can be welded, but whether it is practical or economical to weld. The term "weldability" does not have a universally accepted meaning, but it refers to the effects of the welding heat on the base metal and to the effect of the base metal on the weld deposit. Weldability indicates the amount of precaution necessary for successful welding. Successful welding means making sound joints that are free from defects such as porosity, nonmetallic inclusions, cracks, and hard zones, and with physical properties essentially the same as those of the materials being welded.

In steels, weldability varies greatly and is related primarily to the air-hardening tendency, which is a function of carbon and alloy content. An air-hardening material when welded will have a zone of high hardness and low ductility adjacent to the weld which may fail by cracking during or after welding, depending on the stress condition. Plain carbon steel with a carbon content of 0.25 per cent or under does not air harden appreciably. Other steels which may contain a larger percentage of carbon or chromium, nickel, molybdenum, etc., do air harden, the degree varying with the composition. With them, the properties in the heat-affected area adjacent to the weld are so radically changed that they may not be satisfactory. Heat treatment will restore some steels to their original condition.

There are a number of other properties which must also be given consideration when determining the weldability of a material. Some are discussed in the next few paragraphs.

Certain metals which are hot short (a term indicating brittleness when heated within certain temperature ranges) may crack in the heat-affected area during welding, depending upon the rigidity of the structure.

Because the corrosion resistance of certain materials may be reduced by the heat of welding, a heat treatment after welding may be required to restore it. An example is the carbide precipitation in the heat-affected area when welding stainless steel of 18 Cr, 8 Ni with a non-pressure welding process.

Another property of the base metal which enters into its weldability is its thermal conductivity. Metals like copper and aluminum, which have high thermal conductivity, present difficulties in welding by certain processes because the heat is conducted away from the point of welding so rapidly that it is difficult to raise the base metal to the fusion temperature.

Another consideration is the coefficient of thermal expansion of the metal. Welding metals with a high coefficient of thermal expansion results in a greater amount of distortion, which may result in an unsatisfactory product unless some means is provided to take care of this either in the design or by the methods used in fabrication.

Duralumin is an example of a metal in which a number of the factors mentioned above must be considered. The best physical properties of Duralumin are developed through heat treatment, and the alloy is almost always used in that condition. The welding heat therefore softens the heat treated metal at the weld area by causing overaging in a narrow region around the weld. Duralumin is also hot short, and it has a high thermal conductivity and a high coefficient of thermal expansion, all of which make it difficult to weld successfully.

**16.48. Types of Welds.** There are four basic types of welds, as follows: bead, fillet, groove, and plug. They are illustrated in Fig. 16.54.

The bead weld, Fig. 16.54a, is used for building up surfaces, and for making edge joints in thin materials.

Fillet welds, such as in Fig. 16.54b, are used for tee joints, lap joints, and corner joints. The size of a fillet weld is measured by the leg length of the largest 45° right triangle that can be inscribed within the contour of the cross-section of the weld, as illustrated in Fig. 16.55. The minimum size of fillet weld recommended for general fabrication of several plate thicknesses is given in Table 16.7. When employing an inter-

mittent rather than a continuous fillet weld, the minimum length should be at least four times the size of the fillet, but not less than 1 in. long. It is good practice to place intermittent welds directly opposite each other on both sides of a joint, rather than to stagger them. The maxi-

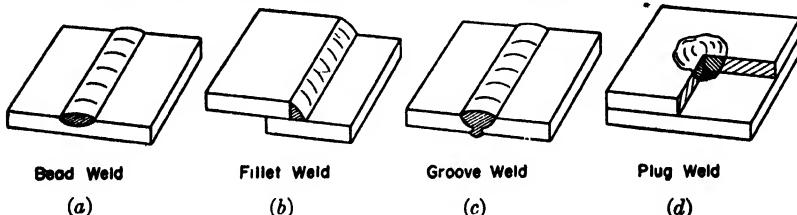


FIG. 16.54. Sketch showing the four basic types of welds.

mum size for intermittent fillet welds should be  $\frac{3}{8}$  in. In making the fillet weld, metal-to-metal contact of the parts should be maintained whenever possible, although, if necessary, a maximum gap of  $\frac{3}{32}$  in. may be permitted for processing. The fillet welds should be so placed that the tensile stress from any bending action falls at the face of the fillet and not at the root where a notch condition exists. This is particularly important where the part may be subjected to shock or fatigue.

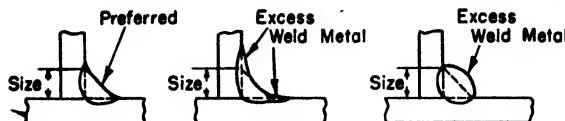


FIG. 16.55. Method of specifying the size of a fillet weld.

TABLE 16.7

<i>Thickness of Thinnest Plate, in.</i>	<i>Minimum Fillet Size, in.</i>
$\frac{1}{8}$ to $\frac{5}{16}$	$\frac{3}{16}$
$\frac{5}{16}$ to $\frac{1}{2}$	$\frac{1}{4}$
$\frac{1}{2}$ up	$\frac{5}{16}$

The cross-section of a groove weld is illustrated in Fig. 16.54c. The size of such a weld is the depth of the groove (usually equal to the plate thickness unless otherwise specified). Welding from both sides with a double groove preparation is to be preferred where accessibility and shop facilities permit because less weld metal is required and a saving in time and materials is effected. There are a number of different groove weld preparations called the square, V, U, modified U, and J, according to their shape. Choice of groove type depends on the type of joint to be welded and the thickness of the parts. Tables 16.8, 16.9, and 16.10 give information on the proper use of these standard

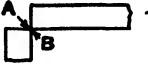
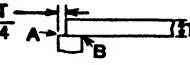
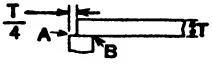
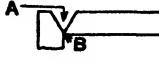
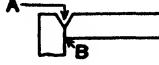
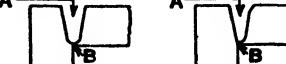
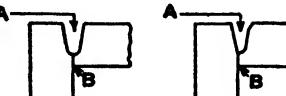
TABLE 16.8. SELECTION OF GROOVE FOR BUTT JOINT

Plate Thickness (in.)	Type of Groove	Weld Depth	One Side	Both Sides (See Note)
$\frac{1}{8}$ to $\frac{1}{4}$	Square	Plate thickness	*	
$\frac{1}{8}$ to $\frac{3}{8}$	Square	Less than plate thickness		
$\frac{1}{4}$ to $1\frac{1}{4}$	V	Plate thickness	*	
		Less than plate thickness		
$1\frac{1}{4}$ to $2\frac{1}{2}$	V U, or mod. U	Plate thickness	* *	 
		Less than plate thickness but $1\frac{1}{4}$ " or greater	 	—
		Less than $1\frac{1}{4}$ "		
$2\frac{1}{2}$ Up	U mod. U or V	Plate thickness	See Above (U or Mod. U)	 
		Less than plate thickness but $2\frac{1}{2}$ " or greater	See Above (U or Mod. U)	 
		Less than $2\frac{1}{2}$ "	See Above (U or Mod. U) (V for Depth less than $1\frac{1}{4}$ ")	 

\* With or without permanent backing strip. Contact the shop to determine whether backing strip is to be used.

Note: " Both sides " preferred to " one side," accessibility and shop facilities permitting.

TABLE 16.9. SELECTION OF GROOVE FOR L-JOINT

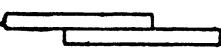
Plate Thickness (in.)	Type of Weld	Weld Depth	Joint Cross-Section
All	Fillet at A *	..	
All	Fillet at B	..	
All	Square groove at A *	Partial penetration	
$\frac{1}{8}$ to $\frac{3}{8}$	Fillet at A *	Partial penetration	
$\frac{1}{4}$ to $1\frac{1}{4}$	V groove at A *	Plate thickness	
		Less than plate thickness	
$1\frac{1}{4}$ up	U or mod. U groove *	Plate thickness	
		Less than plate thickness but $1\frac{1}{4}$ " or greater	
	V groove *	Less than $1\frac{1}{4}$ "	

\* With or without a fillet weld at B.

Note: A small weld at A and B is better than a large weld at A or B.

Where possible, extend one member to form a T-joint and use fillet welds.

TABLE 16.10. SELECTION OF GROOVE FOR T, LAP, AND EDGE JOINTS

Joint	Plate Thickness		Type of Weld	Weld Depth	One Side	Both Sides (See Note)
	A	B				
T*	All	All	Fillet	..		
	$\frac{1}{2}''$ to 1	All	J groove	Plate thickness		—
				Less than plate thickness but $\frac{3}{8}''$ or greater		—
	1" up	All	J groove	Plate thickness		
				Less than plate thickness but $\frac{3}{8}''$ or greater		
Lap	All		Fillet	..		
Edge	$\frac{1}{16}''$ to $\frac{3}{16}''$		Square groove	Partial penetration		

\* With or without a fillet weld on either or both sides of the above T-joints.

Note: A small weld on both sides is better than a large weld on either side.

groove preparations. The U, modified U, and J grooves are recommended for use when welding in the flat position only. Where positioning of the work is not practical, it is recommended that V or double V grooves be used. In view of the effect of positioning on the choice of grooves, it is desirable that the designer work closely with the manufacturer on this matter.

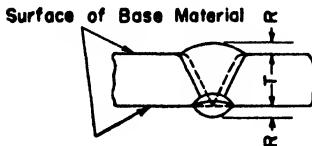


FIG. 16.56. Reinforcement of a weld.

Groove welds can be made flush with the surface of the parts, but when not required to be flush, they should be reinforced a definite minimum amount above the surface of the base material. This minimum amount is designated as  $R$  in Fig. 16.56 and is one-fourth of the plate thickness for plates up to  $\frac{1}{2}$  in. in thickness, and for larger plates is  $\frac{1}{8}$  in. For welding grooves flush, the height of the weld surface can be made within the following tolerances with respect to the surface of the base material.

#### *Surface height tolerance*

For plates up to $\frac{1}{4}$ in. thickness	-0 to $+\frac{1}{16}$ in.
For plates $\frac{1}{4}$ in. and up	-0 to $+\frac{3}{32}$ in.

Of course, the weld surface can be finished off by machining, grinding, etc., after welding, if desired.

Plug welds are used to connect two parts by welding through a round hole or a slot in either one of the parts. Fig. 16.54d is a sketch of a finished plug weld. The hole for this weld was placed in the top member, and after welding a fillet at the junction of the two parts, the welder continued the welding until the hole was filled. In slots, the fillet weld alone is preferred to filling up the slot with weld metal. Plug welds are used for welding stay bolts to thick plates and for strengthening the support of a fixture bolted or welded to a plate. Use of these welds should be regarded as a special procedure, and instructions of a competent welding group should be obtained to assure proper technique in each application.

**16.49. Types of Joints.** Bead, groove, and fillet welds are used in five basic types of joints: the butt, the tee, the lap, the corner, and the edge joint. Each of these joints and the types of weld normally used with it is illustrated in Fig. 16.57.

In selecting the type of joint and its weld preparation, the main factors to be considered are: (1) the nature of the load, (2) the cost of preparation and welding, and (3) the accessibility for welding.

*Nature of Loading.* The loading that must be supported has an important bearing on the type and size of joint to be selected. The type of loading (whether there will be bending stress, or simple tension or shear, etc.), the manner of application (whether the load is steady, vari-

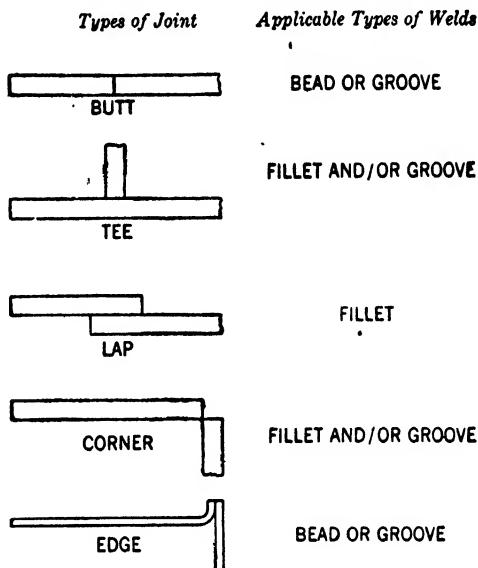


FIG. 16.57. Types of joint, and the applicable types of welds.

able, or suddenly applied), and the magnitude must all be considered. The butt joint is suitable for all usual loads but requires full and complete fusion, particularly when the load is of a fatiguing or intermittent type. The tee joint is used principally for loads which place the welds in longitudinal shear. Loads applied to tee joints produce a nonuniform stress distribution, so in them suitable allowances should be made for the maximum stress intensity when determining the size. This is particularly important for severe impact or heavy transverse loads. Lap joints require practically no machining but are also subject to nonuniform stress distribution. Corner joints and edge joints tend to place the weld in severely stressed positions.

*Cost.* From the standpoint of cost, it is desirable to select a type of joint which requires no preparation (see Fig. 16.58) if the design permits. But where a fillet weld  $\frac{3}{4}$  in. or larger would be needed, a groove preparation might be preferred. Groove preparations for various joints in plates of different thicknesses are given in Tables 16.8, 16.9, and 16.10.

Another item which affects the cost is the nature of the structure.

When considering fabrication by nonpressure welding, it is customary to consider fabricating the structure entirely from plate and wrought shapes, but a similar structure combining castings and wrought forms may be less expensive.

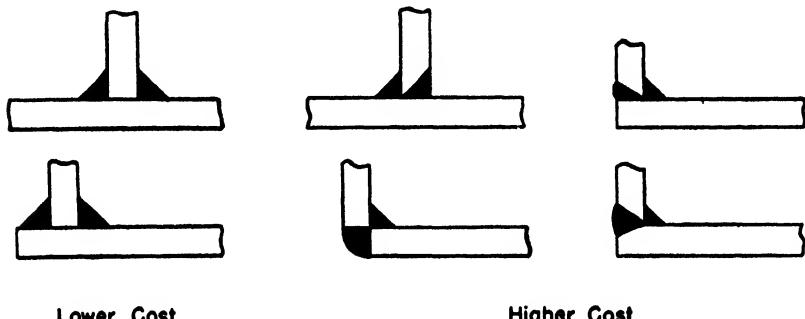


FIG. 16.58. Cost of preparation of tee and corner joints of several different designs.

The cost is also directly related to the amount of weld metal used. The welds should therefore employ a minimum of metal consistent with the load stresses to be carried by the joint, except where tightness, minimum fillet size requirements, appearance, or processing stresses determine the amount of welding.

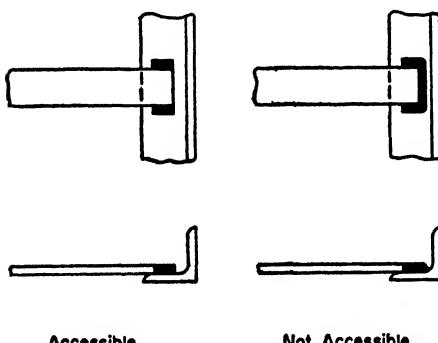


FIG. 16.59. Sketches showing accessible and inaccessible location of weld metal for a design.

*Accessibility.* The parts must be so arranged in the assembly that the welds called for are accessible for welding (see Fig. 16.59) and for non-destructive testing and repairing when they are necessary. It is also a great advantage in the shop to have the welds so designed that they are easily visible to the welding operator and accessible with a minimum of handling.

As the thickness and rigidity of members to be welded increases, the difficulties of welding increase owing to the greater residual stresses concentrated in the weld, particularly in the first pass. Although the difficulties encountered in welding a rigid structure can be overcome to a certain extent by shop procedures such as preheating, and peening, they often can be avoided in the design with a reduction in cost and an

TABLE 16.11

Symbol	Description	Use of Symbol	Illustration
<b>TYPE OF WELD</b>			
~	Bead		
△	Fillet		
	Groove — Square		
▽	V		
U	U		
Mod. U	Modified U		
β	J		
<b>MISCELLANEOUS</b>			
●	Weld in the field		
○	Weld all around (and fillet)		
—	Weld flush (and V groove)		

increase in speed of production. Fig. 16.60 is an example of how a change in design may reduce rigidity and simplify welding.

To facilitate drafting practice in regard to welded construction, the American Welding Society has established and standardized a system of nonpressure welding symbols to be used on drawings. These symbols

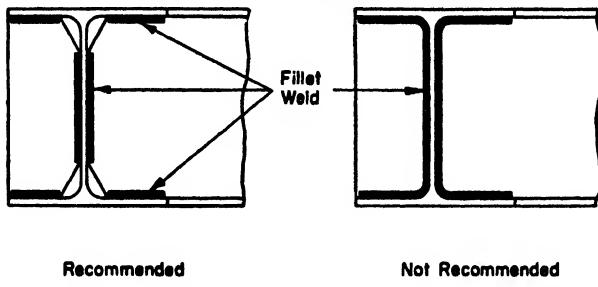


FIG. 16.60. Example of a change in design of a junction of two I-beams which reduces rigidity and simplifies welding.

designate the type, size, location, and specification for each weld without the use of lengthy written instructions. These are illustrated with a few simple examples in Table 16.11. No detailing on drawings is required for fillet welds, but for groove welds the preparation details should be shown.

Engineering Construction codes (A. S. M. E. Boiler codes, Building Codes) for various types of welded structures specify certain minimum acceptable physical properties for the base metal and also for the weld metal. Welding procedures to meet these qualifications are given specification numbers by some manufacturers so the designer can designate the minimum class of welding permitted. When several processes are qualified to meet the physical properties, choice of process is left to the discretion of the shop.

**16.50. Production of Welds. Preparation and Assembly of Parts.** The surfaces of parts at the areas to be welded should be free from dirt, grease, scale, paint, grit from blasting, or any foreign material which would affect the quality of the weld. This includes loose slag adhering to flame cut edges.

The fits between the parts should be in accordance with the type of welds used. For fillet welds, metal-to-metal contact is preferred, but up to a  $\frac{3}{32}$ -in. gap may be allowed. The spacing for groove welds should be controlled according to the shape of the groove. To assure the proper spacing, fixtures may be used for holding as well as locating the work during the welding operation. When the work is large or quantities small, it is often less expensive to position the parts and tack

weld them in place. A tack weld is a preliminary weld, usually of small size and length, for assembly purposes only.

*Prevention of Distortion and Cracking During Welding.* There are a number of techniques that may be employed by the shop to reduce distortion and cracking during welding. Although they are considered shop practice and need not be called for by the engineer, they are of sufficient importance that they should be briefly reviewed here.

(1) A definite sequence should be set up and followed in making welds on any structure. In general, welding should proceed from the point of most restraint to that of least restraint.

(2) All rigid structures and certain materials should be preheated or preheated and concurrently heated. Preheating means heating the work to a predetermined temperature before starting the welding. Concurrent heating means continued heating of the work sufficiently to hold its temperature constant during the welding. When preheating is deemed necessary, the structure should be heated slowly and uniformly (with a maximum temperature difference of 50 C between any two points) to a temperature, for steel, within the range of 100 to 400 C.

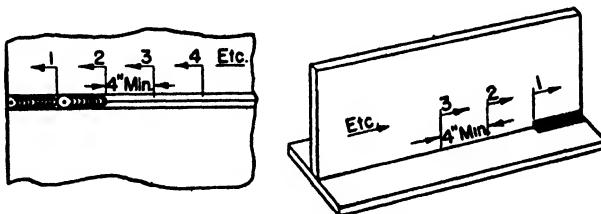


FIG. 16.61. Sketch showing one variation of the backstepping method.

Nonuniform heating may cause distortion or stresses of sufficient magnitude to cause cracking. After welding, the temperature of the structure should be reduced slowly and uniformly. Where such general preheating is impractical and design permits, local preheating may be employed. Where preheating is impractical, it is beneficial to maintain a uniform temperature of 20 C or more and to guard against drafts, water, snow, ice, and sudden changes in temperature of the surrounding atmosphere.

(3) The crater (depression at the termination of an arc weld) in all welds including tack welds should be filled in at the time it is made to reduce the possibility of starting a crack from this point during subsequent welding of the structure.

(4) Backstepping is a sequence of welding that helps reduce distortion and cracking. One variation of it is illustrated in Fig. 16.61.

(5) Peening is the mechanical working of metal by means of hammer blows, as with a blunt nosed tool in an air hammer. Peening may be used to obtain local yielding in the weld metal as an aid in preventing cracks or reducing distortion during welding. The peening operation should not be used in the last pass, or before the removal of all slag, spatter, and weld defects. Care should be taken that peening or chipping of a structure simultaneously with the welding operation does not cause cracking in the weld due to vibration.

*Cleaning.* Slag, flux, and spatter (small metal globules thrown out of the molten pool by the arc) remaining on and immediately adjacent to a pass should be removed by chipping and brushing before depositing each successive pass, and after the final pass.

*Defects.* Any cracks, slag inclusions, or evidences of poor fusion that appear on the surface of a pass should be removed before the next pass is deposited.

Any defects in the finished weld which appear during test or inspection can be repaired by removing all the defective metal and rewelding. If stress relieving has been done before repairing, it should be repeated after repairing. Leaks should not be sealed by peening or caulking. Remove the defective metal and reweld.

An overlap (see Fig. 16.62) is the result of improper welding technique.

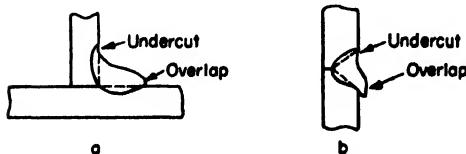


FIG. 16.62. Sketch showing undercutting and overlapping on a tee joint and a vertical butt joint.

Where it occurs, it should be repaired by chipping or grinding, but *not* by peening. Excessive undercut on the finished weld is the result of improper welding technique or carelessness. It may be repaired by welding with a small diameter electrode.

When grinding, chipping, or cleaning welds, care should be taken to avoid undercutting the plate.

*Heat Treatment.* Any heat treatment of a structure after welding should be specified by the engineer. A stress relief heat treatment to relieve residual stresses is advisable where dimensional stability must be maintained in a part to be machined, or where service requirements are severe as in parts subjected to alternating stresses or impact stresses.

*Control of Quality.* In order to obtain consistent and uniform results economically, it is necessary that the manufacturer have (a) qualified procedures, (b) trained and qualified welding operators, (c) proper supervision, and (d) adequate inspection.

In arc and gas welding, the physical properties of the weld metal, such as tensile strength and ductility, will be determined by the particular procedure of welding that is used. It is therefore highly important that procedures be thoroughly investigated and that all welds be made with a definite procedure which has been found applicable. With qualified procedures, the reliability of a welded joint will be determined by the degree to which the weld metal is kept free of foreign materials, e.g., slag and gas, and by the completeness of the fusion to the base metal. Under a fixed procedure of welding, these two latter factors are the only ones over which the welding operator has control. Procedure specifications definitely state all welding conditions for a particular weld, such as base metal to be used, electrode to be used, position of welding, preheat, electrode sizes and currents for each size of joint, and sequence of passes in the weld. Each procedure is qualified by physical tests for tensile strength, ductility, and soundness.

The welding operator should be trained to produce sound welds with the qualified procedure and in the welding position required in production. To insure continuity of his ability to produce these results, his technique may be checked on sample joints once a year or more often. Proper supervision is for the purpose of insuring that the operator has the proper materials and equipment and is working under the proper conditions and with the right procedure to make possible the production of sound welds.

Adequate inspection is one of the most important factors to insuring that operators are consistently following the specified procedure and producing welds of the proper size and strength. Welding inspectors are themselves trained and qualified welders with a considerable amount of welding experience. Their duty is not only to inspect the finished welds for size and for defects of undercutting or overlapping but also to see that operators are following standard procedures in making the welds. In most cases, the soundness and quality of a weld may be closely judged by visual inspection during welding and by the finished appearance of the weld.

*Test.* The types of nondestructive tests used in examining welded structures include (a) X-ray or gamma ray examination for inclusions or other defects, (b) magnetic or fluorescent tests for surface or near surface cracks, and (c) hydrostatic pressure leak tests. Such destructive tests as tests for mechanical properties or corrosion resistance of the weld are normally employed in procedure qualification, but may also be employed on sample parts, or on specimens made integral with the job. When tests are required, they should be called for by the designer.

### ALLIED PROCESSES

**16.51. Gas Cutting.** Gas cutting is a process applicable to ferrous materials' (chiefly to steels) by which severing cuts or rough flame machining cuts can be made economically and with good accuracy. The process is an important adjunct to the fabricating of welded structures, since by this means steel plate and structural shapes may be rapidly shaped and the edges economically prepared for welding. The process utilizes a specially designed oxyacetylene torch with provisions for a central jet of oxygen under control of the operator. The cutting



FIG. 16.63. Portable circular steel-plate gas cutting machine.

action is a combination of the chemical action and erosion of the narrow high-velocity jet of oxygen on the material being cut. The material is locally heated to its ignition temperature by means of the oxyacetylene flame, after which the jet of oxygen is turned on to rapidly oxidize the metal in the direct path of the jet. Erosive action of the jet on the metal melted by the heat of reaction produces a kerf of very nearly parallel sides with a width of approximately  $\frac{3}{16}$  in. Under skilled workmanship with mechanically guided torches, the squareness of the edge may be cut to a dimensional tolerance of  $\pm\frac{1}{32}$  in. for materials 2 in. thick or under, with proportional tolerance for materials up to 26 in. thick. A precision setup will make it possible to obtain still smaller tolerances.

Weld preparations cut by this process are usually plain bevels although

U-groove preparations may be made with special flame gouging equipment.

Welded fabrication of heavy gage steel plate (see Fig. 16.63) and structural shapes has been made economically possible by the oxy-acetylene cutting process where steel castings were formerly used.

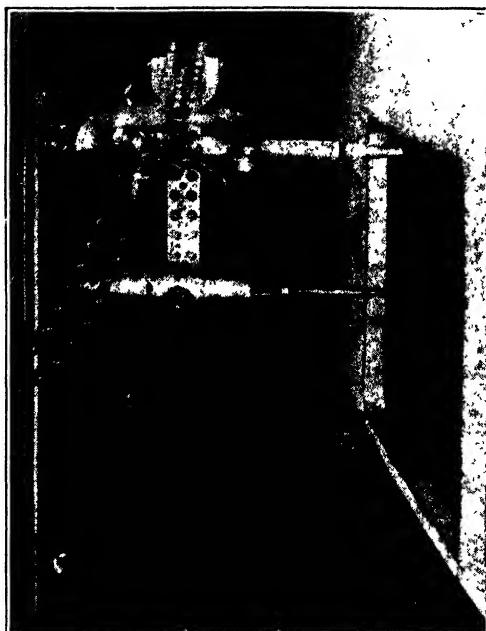


FIG. 16.64. Gas cutting machine using template for gas cutting a rectangular hole in a steel plate in the vertical position.

**16.52. Arc Cutting.** Arc cutting is primarily a melting process by which rough severing cuts may be made on any metal by using a carbon electrode or a coated metal electrode. The process is similar to arc welding but higher currents are used so the base metal is progressively melted and allowed to run out. Arc cutting is sometimes employed in scrapping cast iron and steel structures.

**16.53. Metallizing.<sup>1</sup> Definition.** According to the dictionary, to metallize means "to treat with, especially-to coat with, a metal; to impregnate with a metal or metallic compound." Although this includes electroplating and other processes, it is customary to limit the use of the term to designate only the process of metal spraying. Metallizing, as a process, normally includes the preparation of the work, the

<sup>1</sup> By R. S. Pelton.

spraying on of the metal, and the finishing of the surface by grinding or otherwise.

The metal spray is obtained by atomizing molten metal from wire or powder in a gun similar to the spray gun invented by Dr. M. V. Schoop. The molten metal is blown out of the gun, and each globule assumes a spherical shape in transit from the spray gun to the work. Upon hitting the object, the molten globule quickly flattens, solidifies, and mechanically anchors itself to the preceding sprayed metal. Marked improvements have been made in the art of metal spraying during the past several years, particularly in the method of anchoring to the base metal.

Metalizing is of great value in salvaging machined objects spoiled by mismatching, in maintenance of machinery and equipment by building up worn surfaces, in maintenance of buildings and equipment by replacing metal lost by corrosion, as well as in preventing corrosion and in filling defects in castings, or in applying a different metal to alter the

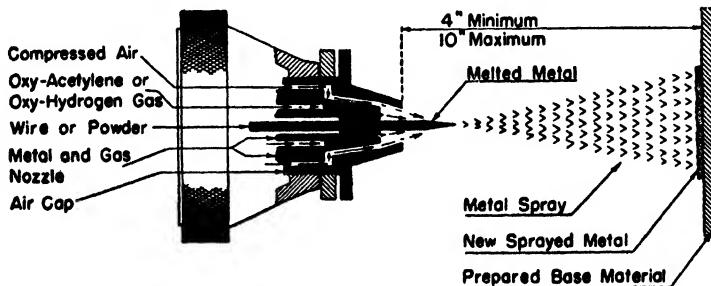


FIG. 16.65. Sketch showing the action of a metallizing gun.

surface condition. The shortage of critical materials and the delays caused by errors in machining can be and are being alleviated by this process.

*Equipment.* There are two types of metallizing guns on the market. The most common type employs metal in wire form. The gun is made up of an oxyacetylene torch with a hole for the wire through the center of the tip, a small air turbine and gears to feed the wire through the tip into the flame, and an "air cap" which encloses the oxyacetylene tip and directs a blast of air to pick up the molten metal and deposit it in atomized form on the prepared surface. This is illustrated in Fig. 16.65.

The less common type of metallizing gun uses powdered metal. With this apparatus, the powdered metal is fed from a special container through a rubber hose to the "pistol" as it is called, and out through the center of the flame, similar to the "wire gun." An air-operated

vibrator on the container helps to obtain a steady feed. The powder spraying equipment is simpler and lighter in weight, but there is difficulty in maintaining a steady feed of powder. Also, with the possible exception of zinc, the metals are more expensive in powder form than as wire, and the deposit efficiency is much lower, that is, more weight of powder is used to obtain a certain weight of deposited metal. The powder gun cannot melt the higher melting point metals such as steel. Its field is limited to the more easily melted metals such as aluminum and zinc (it is also used for nonmetallic substances such as rubber, certain plastics, and low melting point vitreous materials).

Practically every metal that is available in wire form (except tungsten) has been sprayed in a wire gun. When spraying the metals of lower melting point, the gun may be operated with hydrogen, city gas, or propane in place of acetylene. The deposit efficiency of the wire gun ranges from about 65 per cent with easily oxidized metals such as zinc to about 90 per cent with iron and steel. The remainder of this discussion will refer to this type of equipment.

*Nature of Deposit.* The sprayed metal does not usually *fuse* onto the surface where it is deposited. There is no welding action. The deposited metal is usually held in place by adhesion to a rough surface, as plaster adheres to a wall. The structure is not unlike a series of fish scales piled one on the other in an irregular fashion with some trapped oxide and porosity. This porosity is a disadvantage when the coating is to resist the penetration of fluids, but it has proved to be a real advantage in lubricated bearings.

The density of the deposited metal is about 10 per cent less than that of the same metal in cast form. Ductility and tensile strength are also lower, but the compressive strength is good. Metal coatings have withstood much abuse in press fits and have served well as bearing metals.

*Surface Preparation.* There are certain definite requirements which must be observed to obtain a good bond between the deposited metal and the work.

(1) The surface to be sprayed must be perfectly clean and dry. A freshly machined surface (without lubricant) is preferred.

(2) The surface should be roughened considerably. For thin coats (not over 0.010 in. thick) blasting with sharp angular grit can roughen the surface satisfactorily. Heavier coatings, at least 0.030 in. thick, are usually preferred when they are to be machine finished. The surface to receive such a coat should be prepared with grooves as described later. Blowholes should be opened up, given a dovetail edge and blasted to clean and roughen the interior.

(3) The sprayed metal must be finely atomized so that the particles

are small enough to penetrate the smallest openings of the prepared base metal and so bond to it. Properly atomized metal penetrates the smallest openings and packs surprisingly tight.

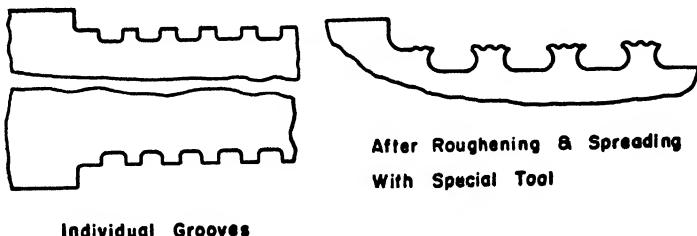


FIG. 16.66. Type of groove preparation used for anchoring metallized surfaces that are to be machine finished (sketch of roughened grooves is to a larger scale than original grooves).

(4) Special preparation of carbon, pressboard, etc., is usually unnecessary except to be sure that they are clean and dry. (Such materials as cloth, paper, and pressboard are safely metallized because the flame is



FIG. 16.67. A metallizing gun being adjusted in a lathe setup for spraying a shaft.

held far enough away and the particles of metal are so small that they chill before they burn the material.)

The type of preparation recommended for surfaces to be machine finished is illustrated in Fig. 16.66. When properly applied, it is impossible to peel the coating off the base metal. This has become the

most common preparation on wrought materials, especially shafts and cylinders that can be turned in a lathe (see Fig. 16.67). The area to be sprayed is first turned undersize, then grooved, and then the tops of the bands are rolled by a special tool which spreads them to form dovetails and at the same time thoroughly roughens them. There is no limit to the thickness of coating that can be applied, but to date, there seems to be no service data available regarding thicknesses greater than 0.040 in. on journal surfaces.

As a general rule, a complete band should be applied to a shaft or in a bore, rather than to metallize a spot. Feather edges should always be avoided by dovetailing or square edged undercutting.

*Applications* Metallizing is used for a variety of applications such as the application of decorative metallic coatings, electrical shielding, soldering areas on nonmetallic parts, improvement of electrical connections, the forming of molds, and even for the placing of brazing alloys previous to heating. However, the majority of industrial applications are either for corrosion resistance or mechanical sizing or surfacing.

Many corrosion problems have been solved by application of the correct metal. There are two distinct problems: (a) Zinc and aluminum being anodic to iron and steel furnish good protection to it regardless of porosity. (b) On the other hand, when lead or stainless steel is used on mild steel the application must be thick enough to prevent penetration of the corrosive agent to the base metal or the part must be treated to close the pores. A good wire brushing is commonly used to close the pores of sprayed lead.

There are also two distinct fields of service: one at room temperature and the other at elevated temperatures. Aluminum is usually preferred to protect steel at higher temperatures. For maximum protection a sprayed aluminum coating can be processed to produce an alloy coating comparable to a calorized surface.

Bearing specialists in England have investigated a wide range of bearing metals sprayed versus cast and wrought, and they report<sup>1</sup> that sprayed steel journals in white metal bearings will carry two to three times as much load as solid steel journals. Usually the coefficients of friction were lower with sprayed steel, which ran seven times as long after the oil supply was cut off.

Surfacing applications include coating of parts such as piston rods, rams, slides, and cams with wear-resisting materials. High carbon steel, nickel, any type of stainless steel, or bronze can be applied. The

<sup>1</sup> *Metal Industry (London)*, Oct. 29, 1937, v. 51, pp. 427-430; *Engineering*, Dec. 31, 1937, v. 144, pp. 757-758; *Metal Industry (London)*, Apr. 14, 1939, v. 54, pp. 415-418.

particles of steel are chilled so suddenly that carbon steels develop maximum hardness when sprayed.

Many of the applications mentioned have only recently been developed, but in them the metallizing process has made possible techniques which can be conveniently accomplished in no other way. Metallizing shows promise for other new and important developments in the future.

### REVIEW QUESTIONS

1. Define the brazing process. In a brazed joint is there any alloying between the filler and the base metals?
2. Upon what factors does the strength of a brazed joint depend? How does the strength of a brazed joint compare with that of the filler or the base metal?
3. What four common types of filler metal are used for brazing? Which has the highest melting temperature? For what type of work are spelter and bronze brazing and aluminum brazing used?
4. What are the three fundamental types of joints? By what methods may the filler metal be applied to the joints? For general work, what joint allowances (clearance or interference) are preferred for highest strength with each of the four types of brazing materials?
5. What is the purpose of a brazing flux? How may it be applied?
6. What three requirements outline the heating problem? Name the methods of heating commonly employed in the brazing process, and give an example of a product that might be brazed with each.
7. How does soldering differ from brazing?
8. Compare the strength of brazed joints with that of soldered joints at room temperature. How do they compare at slightly elevated temperatures (e.g., 100 to 125 C) and for long time loading?
9. What class of welding process is known as resistance welding? Name some of the advantages of resistance welding over the other welding processes.
10. What general equation expresses the heat generated in the weld when there is no arcing or combustion? Indicate with a sketch the three resistances which make up the total resistance which is effective in generating heat for the weld.
11. What are the effects of applying pressure to the weld?
12. What is phase-shift control? Why is synchronous switching important, especially when welding stainless steel and nonferrous alloys?
13. How is the welding current localized at the weld in spot welding? In projection welding? In seam welding? In butt welding? Give an example of an application of each type of welding. How does upset butt welding differ from flash butt welding and for what materials is each used?
14. Describe the purpose of pulsation welding. What are percussion welding and stored energy welding, and with what processes is each usually used?
15. Why is the cleaning of metal important for successful resistance welding?
16. What are the three main types of nonpressure welding processes? Which of the arc welding processes is most used?
17. Why is a coating used on electrodes for metal arc welding?
18. Describe how the heat is transferred to the work in atomic hydrogen welding. For what type of work is this process especially applicable?
19. Name some of the advantages of the gas welding process.

20. What are the effects of welding heat on the base metal? Define weldability and name some of the properties which affect it.
21. Name and describe the four basic types of welds and the five basic types of joints. Explain some of the factors which influence choice of the type of joint.
22. What are some of the shop techniques that may be employed to limit distortion and prevent cracking?
23. Describe flame cutting, arc cutting, and metal spraying. Discuss the types of applications where each of these processes is used.

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## CHAPTER XVII

### MACHINING

By W. L. BOND and D. L. CLARK<sup>1</sup>

**17.1. Introduction.** Machining is the art of using machine tools and cutting tools in combination to reduce a piece of material to some specified shape and dimensions.

It is the responsibility of design or drafting engineers to visualize and specify those final shapes and dimensions in an economical and practical manner. The machinist, who may be the executive, supervisor, or any other person responsible for the detailed machining of parts, transmits these specifications into the finished product.

In normal times the success of the art of machining, as with other processes, depends largely upon its economy. The separate items of the cost of machining may be divided, very generally, as follows: equipment, tool wear and breakage, waste material, and time (labor). Each of these items is directly or indirectly the responsibility of the designer, and in order to obtain a proper balance among them it is necessary that he have and employ a fundamental working knowledge of machine tools and methods. To this end, the purpose of this chapter is to guide the engineer in designing from a manufacturing point of view. The fundamental machine tools and processes will be discussed individually, each section containing a general description, the ordinary applications, and the special design points to be considered. Wherever practicable, it will be pointed out how the items of manufacturing cost, particularly the latter three, may be effectively controlled by proper design.

**17.2. Surfaces and Finishes.** The surface of a solid material generally consists of a number of high and low spots, sometimes visible to the naked eye, sometimes microscopic. The vertical distance between these high and low spots may be referred to as surface thickness, roughness, or depth. When such surfaces with "thickness" intersect to form lines and points, the lines have width and depth as well as length and the points are small volumes.

Machining operations produce surfaces which have a great latitude of surface roughness, depending on the material and the machining

<sup>1</sup> Prepared under the general direction of B. G. Tang, General Superintendent, Schenectady Works, General Electric Company.

process itself. Surfaces may be machined to specifications by comparison with actual sample blocks of surfaces falling within specified limits of surface roughness. These blocks may be calibrated by an instrument similar to a phonograph pickup. This instrument employs a very fine point which follows the vertical deviations of the surface as it is moved along and indicates a value corresponding to the average deviation of the surface. This average deviation is equivalent to one-fourth to one-third of the actual peak-to-valley depth for most surfaces and is measured in micro-inches (inches  $\times 10^{-6}$ ). Measurement of surfaces in this manner allows accurate classification of finishes, although no national standard has been set up as yet.

For particular applications, factors other than surface roughness may influence the utility of a surface. For instance, the direction of tool marks, or "lay," considerably affects the operation of some bearings and valves; a metal-to-metal seal may be unsuitable because of waviness (lack of flatness), although its surface roughness is within specified limits.

**17.3. "Laying Out" and "Setting Up" Material.** Before a piece of material can be machined, the location of the objective surface, which as yet does not actually exist, must be determined with respect to the actual surface of the material. When this has been accomplished, the material is said to be *laid out*.

In all machine work, dimensional accuracy is limited by the roughness or "thickness" of surfaces and the fineness with which lines and points can be established. Consequently, layouts made with scribes, dividers, etc., are relatively inaccurate since the lines and points are of finite width. So far as practicable, such layouts should be used for general location only. More accurate measurements are obtained by use of gages, as explained in a later section.

When the material has been laid out, it must be suitably located and held in the machine tool so that its motion with respect to the cutting tool can be controlled. When this has been accomplished, the material is said to be *set up*.

In practice, the layout and setup of a piece of material are often so closely interdependent that a distinction between the two is difficult to make.

The designer can contribute greatly to the ease with which work may be laid out and set up. For example, in the design of castings, a reference plane is desirable as a common starting point from which to make measurements in drafting, pattern making, casting, machining, and inspecting. This plane can be designated on the drawing as the *pattern checking point* and would be in reality an unmachined surface selected

for its strategic position in the mold and for its location with reference to holding for machine operations. Since some castings are machined with reference to more than one plane, it is desirable to indicate a pattern checking point in each reference plane.

Similarly, to aid setups, the engineer may call for lugs or bosses whose sole purpose is to provide a place for clamping during machining. Being able to visualize when and where such things will be of assistance to the machinist is a mark of a good designer.

**17.4. Metal Cutting.** Tremendous forces are involved in the shearing or tearing action with which a metal chip is peeled off in machining operations. The magnitude of these forces varies with the material, tool shape, and size of chip. Investigations by F. W. Taylor show that 35 to 99 tons per sq in. of chip cross-section (depth of cut multiplied by its width) were required for machining cast iron, and 92 to 168 tons per sq in. for machining forged steel.

Even with a light chip, the forces developed in cutting cause appreciable deflection of the tool and the work. The more accurate the dimensional requirements, the smaller these deflections must be, and a number of light cuts must be used, thereby increasing the cost. Hence, the engineer should make certain that his design (*a*) is rigid enough to withstand the machining forces without excessive deflection, (*b*) is capable of being held firmly to the machine tool, and (*c*) provides sufficient working space for machining with sturdy, rigid, and well-supported tools. Failure to meet any of the above requirements limits the size of the chip that can be taken and nearly always increases the cost.

The large amount of heat generated in metal cutting and grinding is dissipated either in a stream of cooling fluid or by conduction into the tool and work. Various cooling fluids (coolants), such as light oils and water containing rust preventives, are used. The type of coolant selected depends on the material being machined and the cutting speed. The use of a coolant generally permits more rapid production and serves to lubricate the cutting action, to produce a better finish by washing away chips which would otherwise score the surface, and to remove generated heat which might otherwise be the principal factor limiting the chip size.

The factors, then, that limit the maximum size of chip that it is practicable to take are:

- a.* Deflection of work.
- b.* Deflection of tool.
- c.* Anchorage of work.
- d.* Type of material being cut.
- e.* Dissipation of heat.
- f.* Horsepower capacity of machine.
- g.* Cutting speed.

When a cutting tool is fed into the work at the start of a cut, there is, at the instant of contact, an impact or blow between the edge of the tool and the work. This impact tends to break small particles from the cutting edge and in this way dull the tool. Designs which require machining by intermittent cuts should be avoided since they cause continuing impacts of this type and result in tool wear and breakage. The sudden application and sudden release of pressure also cause inaccuracy in the cut surface at the points of application and release.

The minimum thickness of chip that may be removed practicably and accurately must be greater than the combined thickness of the surface to be cut and the cutting edge of the tool. Otherwise a series of intermittent cuts will result, each with attendant inaccuracy and destruction of the cutting tool.

The design of parts made from castings, forgings, etc., which have a hard abrasive surface should provide for enough surplus material so that the chip will be thick enough to include not only the actual surface, but also whatever unduly hard material may be directly underneath. Such designs eliminate all pit marks and scale on the finished surfaces and do not cause excessive tool wear.

A few general points that should be remembered in designing for most machining operations might well be summarized here.

- a. Provide for ease in laying out and holding work.
- b. Design for minimum number of setups or operations.
- c. Avoid intermittent cuts.
- d. Do not specify greater accuracy and better finish than that required.
- e. Design with a particular machining method in mind but do not tie the design to that method alone.
- f. Be consistent in establishing tolerances of related dimensions.

**17.5. Cutting Tools.** Cutting tools are of two general classes: (a) Single point tools, such as lathe and planer tools, which have but a single cutting edge, and (b) tools such as milling cutters and reamers which have a number of cutting edges.

A single point lathe tool is shown in working position in Fig. 17.1. The front and side clearance angles indicated are to minimize friction between work and tool. The angles used depend on the material being cut.

Fig. 17.2 shows some modern tungsten carbide tipped tools with single and multiple edges.

Cutting tools are made from various materials, some of the more common of which are listed here.

**HIGH CARBON STEEL.** 0.9 to 1.2 C. Operates up to 400 F. Confined mostly to taps, dies, and small drills where production is small or where excessive breakage is apt to occur. Very generally used for wood and other soft material.

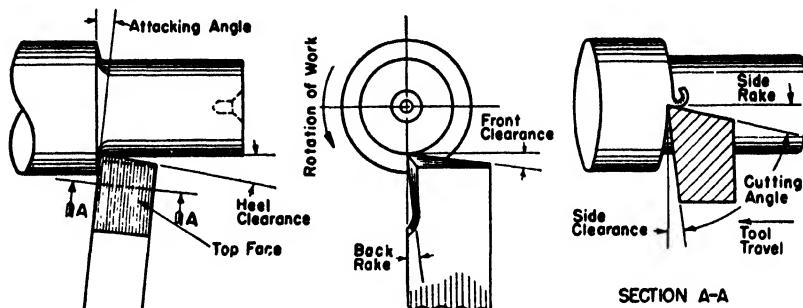


FIG. 17.1. A lathe tool in a typical position relative to the work.

**HIGH SPEED STEEL.** A typical steel contains 18 W, 4 Cr, 1.0 V, and 0.6 C. It will operate almost up to a red heat, and is used very widely for general metal cutting.

**NONFERROUS ALLOYS.** Stellite is an example. It contains 13.5 W, 40.5 Co, 32 Cr with smaller percentages of Ni, Mn, C, and Fe. These alloys remain hard up to 1500 F, a property known as *red-hardness*. They are used in high speed operations.

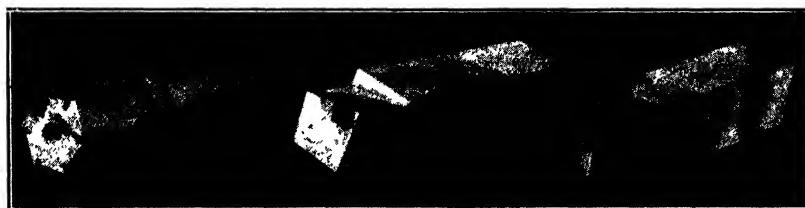


FIG. 17.2. Single point and multiple edge tungsten carbide tipped cutting tools.

**CARBIDES OF TUNGSTEN, TANTALUM, ETC.** An example is Carboloy and a typical analysis is 5.3 C, 12.7 Co, and 81.4 W. Used for high production, high speed work or where the same tool can be used on a number of different jobs. Also used for cutting very hard, nonmetallic materials. Because of high cost and brittleness, bits are generally brazed to a carbon steel body. See Fig. 17.2.

**ABRASIVES — ALUNDUM.** Silicon carbide, SiC and aluminum oxide,  $\text{Al}_2\text{O}_3$ . Are generally bonded to form grinding wheels and honing tools. Each grain constitutes a small cutting bit in itself.

**DIAMONDS.** Used as a single point tool in dressing grinding wheels and finishing nonferrous materials, and as an abrasive for lapping very hard materials.

**17.6. Drilling.** The twist drill with either a straight or tapered shank is probably the most nearly standardized and the most widely used of all metal cutting tools. It is essentially a roughing tool and is used with all machine tools that machine holes in solid materials.

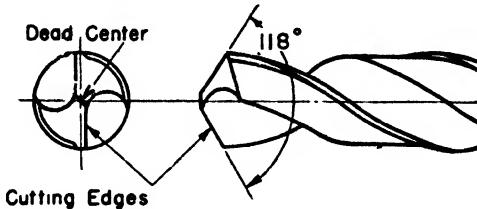


FIG. 17.3. Twist drill.

Figure 17.3 illustrates a typical twist drill for drilling metal. The point angle shown is nearly standard for drilling cast iron and steel and is changed very little for drilling other metals. For plastics this angle may be much sharper, on the order of  $90^\circ$ . The two lips are true cutting edges with definite rake and clearance angles. The dead center has no rake angle and is not a true cutting bit. Its action may be considered as a combination of scraping and wedging. For this reason a high pressure along the axis of the drill must be applied to the dead center in order to force it into hard material. A sharp 1-in. drill, for example, may require as much as 1 ton thrust pressure to penetrate steel with a reasonable feed and this pressure may be increased as much as 50 percent as the drill becomes dull.

A comparatively low side pressure applied at right angles to the axis of the drill will deflect the point. After the point of the drill has completely entered the material, the sides of the hole serve to guide the point. Two methods are used to help prevent deflection of the point as the drill starts into the material. For repetitive work, a fixed bushing, in which the body of the drill revolves, is provided near the point of the drill. Where the quantities are small, a cone shaped depression (center punch mark) is made in the material. In addition, the two drill lips must be symmetrical with respect to each other so that their side pressures will balance. It is equally important that the surface of the material, where the drill is started, be so shaped that balanced side pressures of the two lips can be maintained. When it is necessary to start a hole on the sloping surface of a casting (Fig. 17.4a), a boss should be provided, as illustrated in Fig. 17.4c, if such a boss can be

allowed by good pattern and foundry practice. When it is not practicable to provide a boss on a casting or other material, a flat spot larger than the body of the drill should be machined with another cutting tool (Fig. 17.4b).

A burr is formed around a hole by the action of the drill as it starts into the material. This is quite marked if the material is tough and ductile. If the hole is drilled through the material, a burr is also formed around the hole as the drill point breaks through the surface. Where such burrs may prove a hazard to the safety of workmen or where they may interfere with other parts, they are removed by means of a countersink. Break-through on uneven surfaces (Fig. 17.5a) gives a high mortality rate on drills and should be avoided, if possible, as in Fig. 17.5b. It is better, however, to allow break-through on uneven surfaces than to call for a flat-bottomed blind hole, as illustrated by Fig. 17.7a. This



FIG. 17.4.



FIG. 17.5.

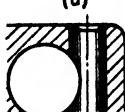
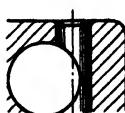


FIG. 17.6.



FIG. 17.7.

#### Hints in Design for Drilling.

requires an additional operation to remove the material left by the drill point and results in additional expense as compared with a bottom shaped as in Fig. 17.7b, which illustrates a hole rough drilled with no additional operation except countersinking.

When a design calls for the use of a drill, the following points should be kept in mind.

- a. Specify a drill of standard size.
- b. Avoid the use of unusually small drills.
- c. Avoid deep holes.
- d. Allow space for the drill point at the bottom of blind holes.
- e. Avoid blind holes when possible — drill through.
- f. If it is necessary for the point of the drill to break through, as in drilling near an internal hole, keep the center of the drill in the material. (See Fig. 17.6 a and b.)

- g. Avoid starting a drill on a surface not perpendicular to the drill.
- h. Avoid drilling extremely hard materials.
- i. Remember that a drill is a roughing and not a finishing tool.
- j. Provide space for the countersink when it is to be used.

**17.7. Reaming.** A straight reamer is a cutting tool used to finish or semifinish the surface of a cylindrical hole. Fig. 17.8 illustrates typical straight reamers with straight and helically shaped flutes and blades. Each blade is chamfered at its end, where all of the cutting is done. The rest of the blade serves to guide the cutting end and burnish

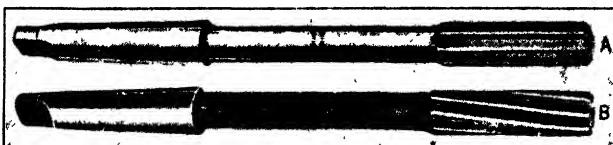


FIG. 17.8. Straight reamers, with straight and helical flutes. (*Courtesy Union Twist Drill Company.*)

the surface of the hole. The chamfer is about  $\frac{3}{32}$  in. to  $\frac{1}{8}$  in. on standard reamers, which leaves a corresponding bevel at the bottom of a blind reamed hole. If no allowance is made for this bevel, a special reamer with almost no chamfer must be used in a second operation.

A taper reamer is used to rough taper a cylindrical hole and to finish or semifinish the conical surface thus formed. It consists of straight or spiral shaped blades on a main body having a conical form. In designing remember:

- a. Do not call for a square corner at the bottom of a blind reamed hole — make allowance for the chamfer of the reamer.
- b. Use through holes wherever possible.
- c. For accurate spacing between reamed holes, the drilled holes must be accurately spaced.

**17.8. Counterboring and Countersinking.** When a drilled hole is to be enlarged concentrically for a portion of its length, a counterbore may be used (Fig. 17.9a). It consists of a series of blades arranged to cut on the ends only and a smooth pilot slightly smaller than the drilled hole.

A spotfacing tool (Fig. 17.9b) is similar to the counterbore and is used primarily for producing a shallow, annular, finished surface such as the surface to mate with the head of a bolt or nut. By spotfacing at required places, the complete finishing of a surface may often be avoided.

A countersink is used to chamfer the edge of a hole as shown in

Fig. 17.9c. This may be done for flush-mounting a flat-head screw or it may be simply a burr-removing operation.

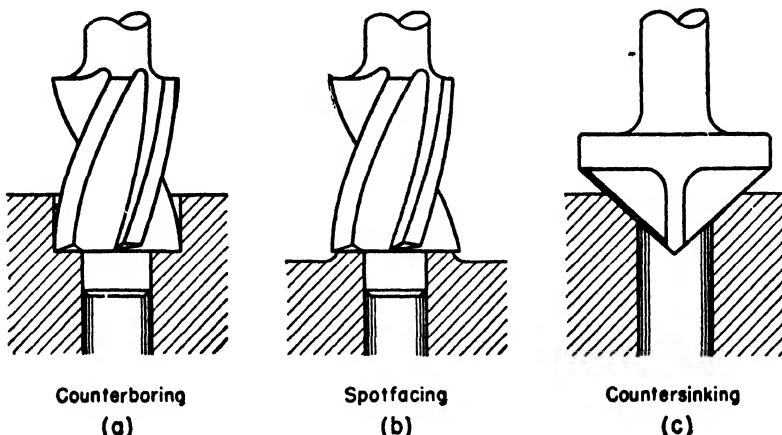


FIG. 17.9. Some other drilling machine operations.

**17.9. Tapping.** A tap is a finishing tool used to produce an internal thread in a hole. It generally consists of several cutting blades which are part of a supporting body.

The lower portion of Fig. 17.10 illustrates a standard straight tap. The end of the straight tap, which enters the hole, must be beveled for a distance equal to two to four times the distance between threads,

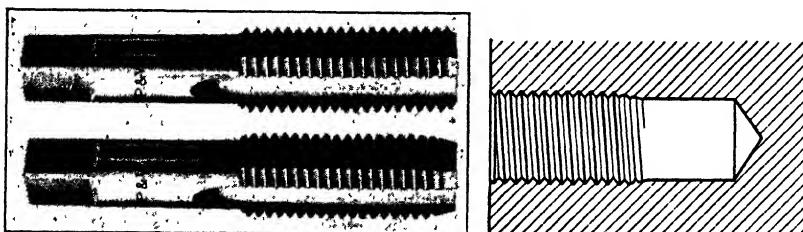


FIG. 17.10. Standard taps. (Courtesy Pratt & Whitney.)

FIG. 17.11. Economical design of tapped blind hole.

depending upon the material to be cut. All the cutting is done by this beveled portion. The remainder of the threaded portion serves to guide and drive the cutting end. As the tap advances it pushes most of the chips ahead of it. Space for chips should be provided at the bottom of a blind hole comparable to the volume of chips. The fine line in Fig. 17.11 indicates the end of the tap at the time the thread was com-

pleted. The space between this line and the bottom of the hole is for chips, the amount of which will vary with conditions. For example, a coarse thread tap of small diameter in cast iron, where the depth of completed thread should equal  $1\frac{1}{2}$  times the nominal diameter of the tap, requires for economical machining a hole equal in depth to approximately four diameters of the tap drill. Where a thread must be close to the bottom of a hole, a tap so chamfered that it will leave only one incomplete thread, as shown in the upper portion of Fig. 17.10, can be used as a second operation. Such a tap wears rapidly, and its use should be avoided.

A taper tap is used to machine an internal taper thread such as a pipe thread. It is chamfered at its small end for a distance equal to 4 or 5 times the distance between threads. The cutting is done by this chamfered end and also by the entire threaded portion of the tap. A taper tap of small size can often be used in a drilled hole. The larger sizes, however, may require a tapered hole.

For the economical design of internal threads the engineer should, if practicable:

- a. Specify a countersunk hole.
- b. Specify a standard tapped thread.
- c. Use a through hole.
- d. Allow space for chips and incomplete threads at the bottom of a blind hole.
- e. Avoid threads of coarse pitch, small diameter, and excessive length.

**17.10. Drilling Machines.** *Vertical Spindle Drilling.* The most common drilling machine is the vertical spindle drilling machine (Fig. 17.12) and it is used for both general and repetitive work. The work

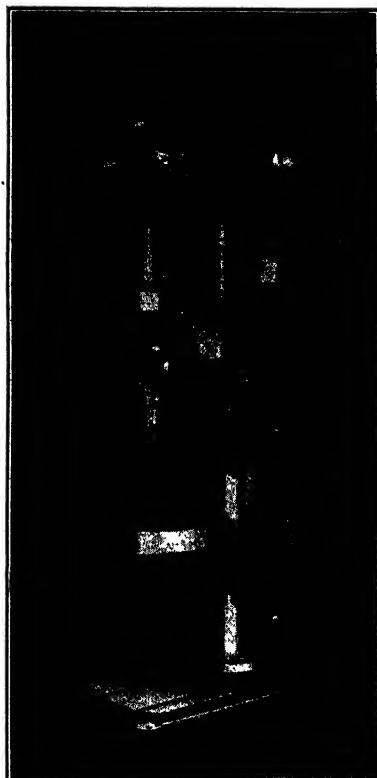


FIG. 17.12. Vertical spindle drilling machine. (*Courtesy Machinery Magazine.*)

may be held on the vertically adjustable work table by means of a vise (Fig. 17.13) or by clamps. For production work, special jigs for holding the work and guiding the tools may be used instead. In operation, the work is stationary and the spindle feeds the tool vertically to the work. A standard tapping attachment may be used in this machine.



FIG. 17.13. Machine vise. (*Courtesy Cincinnati Milling Machine Company.*)

vertical machine. This is a repetitive machine tool particularly adapted to successive operations involving drilling, reaming, countersinking, and tapping.

*Gang Drilling Machine.* This machine consists of several independent spindles mounted on one table. Each spindle holds a tool and is similar in operation to the



FIG. 17.14. Multiple spindle drilling machine operation. Note the special jig used to hold the work and guide the drills. In the foreground, parts are shown before and after drilling. (*Courtesy North American Aviation, Inc.*)

*Multiple Spindle Drilling Machine.* There are many types of multiple drilling machines. The most common are those in which a group of spindles, arranged vertically, can be adjusted for horizontal spacings and height (see Fig. 17.14). The work, held in a jig on the table, is fed upward against the cutting tools, all of which cut in unison.

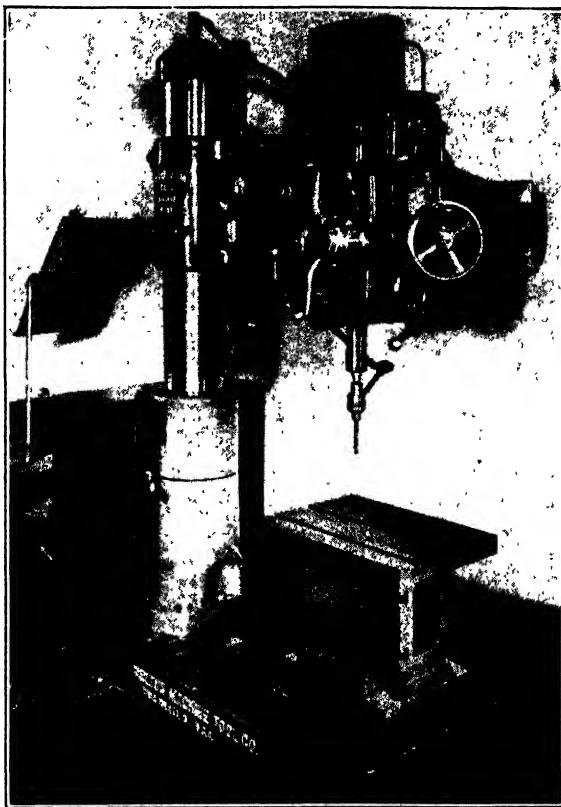


FIG. 17.15. Radial drilling machine.

*Radial Spindle Drilling Machine.* The radial drilling machine (Fig. 17.15) is a general purpose tool designed to perform drilling operations on work which is too heavy and too large to be handled on the vertical spindle machine. It consists of a bed, a column, an arm, and a drilling head which is readily adjustable both radially about the column and vertically to suit the height of the work. In operation, the work is clamped to the bed, and the drilling head is adjusted to bring the cutting tool into the proper position so that it can be fed vertically into

the work. Taps of large diameter are removed by reversing the main driving motor. Since control of this reverse motion is not as positive as that of a tapping head, special care should be taken to allow ample space at the bottom of blind tapped holes and to avoid the use of excessively small taps when a drilling machine of this type is to be used.

**17.11. Engine Lathe Work.** The engine lathe (Fig. 17.16) is one of the most useful and versatile of all machine tools. Since the basic lathe operations and methods of supporting work are applied to a good many more specialized machine tools, considerable attention will be given to this equipment.

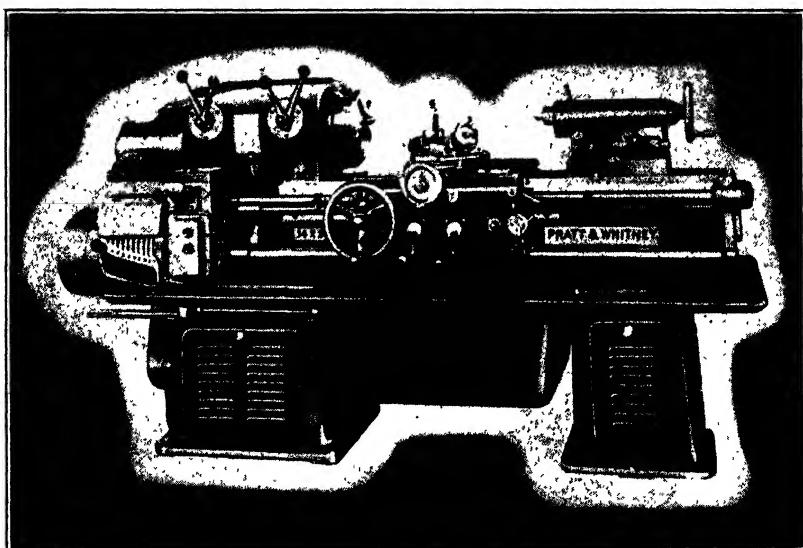


FIG. 17.16. Engine lathe. (*Courtesy Pratt & Whitney.*)

The fundamental lathe operation is turning cylindrical forms by rotating the work against a cutting tool moving parallel to the axis of rotation. Plane surfaces are obtained by supporting the work on a chuck or faceplate and moving the tool perpendicular to the axis of rotation. Drilling, reaming, boring, tapering, contouring, and threading operations can also be performed.

It is important that the engineer be thoroughly acquainted with the ways in which work may be mounted for machining. Following is a discussion of the common methods of holding work.

**Between Centers.** Comparatively long work such as a shaft is provided with countersunk holes in the ends which engage the centers of

the lathe as shown in Fig. 17.17. A *dog* clamped to the work near the driving spindle end engages a faceplate attached to the spindle and transmits the motion to the work. Wherever possible, the countersunk centering holes should be specified in the finished piece, because an extra cutoff and facing operation is needed to remove them.

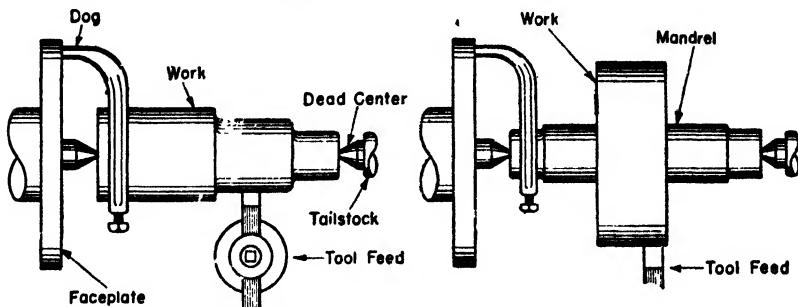


FIG. 17.17. Lathe work mounted between centers.

FIG. 17.18. Lathe work mounted on a mandrel.

*On a Mandrel.* To finish external surfaces accurately concentric with an already finished bore, the work is pressed onto a hard, polished, slightly tapered shaft known as a *mandrel* (Fig. 17.18). This, in turn, is rotated between centers while machining proceeds.

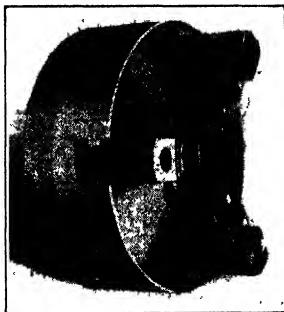


FIG. 17.19. Universal chuck.



FIG. 17.20. Faceplate.

(Courtesy Jones & Lamson Machine Co.)

*On a Chuck.* Short work is conveniently held in *chucks* screwed onto the end of the spindle. One type of chuck, known as an independent chuck, has four clamping jaws each of which may be moved radially independent of the others. This enables pieces of irregular outline to be held and provides for accurately centering symmetrical work.

By a simple change, the jaws may be turned around in their slots to provide internal gripping (Fig. 17.46) and to accommodate small parts. The universal chuck, Fig. 17.19, has three or four jaws which move in and out in unison so that symmetrical work is automatically centered. The jaws in these chucks may also be turned around.

*On a Faceplate.* If the shape of the work does not permit chucking, it may be clamped to a large faceplate (Fig. 17.20) which is attached to the end of the spindle.

*In a Spring Collet.* Fig. 17.21 illustrates a spring collet for holding bar material or tubing. Its use is generally limited to material having a comparatively smooth surface and a standard diameter or shape. The jaws are tightened on the work by drawing the collet proper into a tapered sleeve in the lathe spindle. When the chuck is relaxed, the jaws spring open slightly, releasing the work.

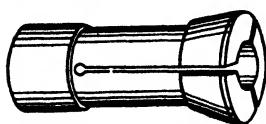


FIG. 17.21. Spring collet.

Collets are convenient for centering work for a second operation. They are extensively used on high production work, where centering

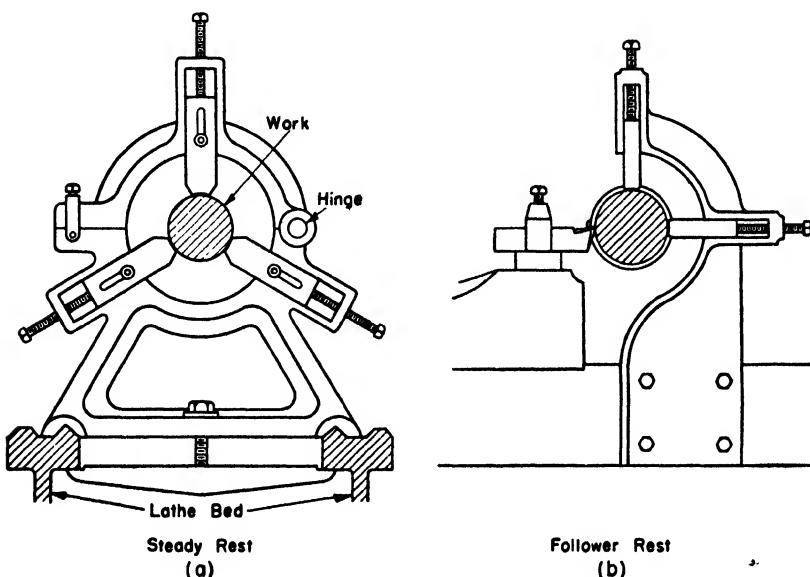


FIG. 17.22. Supports for lathe work.

must be done very quickly, and are particularly adapted to automatic machines. Spring collets are also made for square, hexagonal, and other shapes of bars and tubing.

*On an Expanding Mandrel.* An expanding mandrel is used to hold work on an internal diameter. It is similar in principle to a spring collet. Three jaws are arranged to expand outward and clamp the work as a tapered pin is forced inward.

*On Special Chucks.* For production work chucks are sometimes made up with jaws which conform to irregular outlines of the work. Special chucks may be operated hydraulically or by compressed air for rapidity in mounting and holding work.

*Steady and Follower Rests.* Very long slender work held between centers or in a chuck is unable to withstand machining forces without excessive transverse deflection; hence an additional support must be used. This may be either a steady rest or a follower rest. The former (Fig. 17.22a) has three adjustable jaws which rest on a carefully turned spot near the center of the work's length. The body of the steady rest is clamped to the lathe bed. The follower rest (Fig. 17.22b) has two jaws which rest on the finished diameter just back of the tool. It is fastened to the carriage and follows along with the tool.

As a rule, work between centers must be supported by a rest when its length exceeds 12 times its diameter. For work held in a chuck, the unsupported length should not be over two to four times the diameter.

**17.12. Lathe Operations.** Several common lathe operations are illustrated in Fig. 17.23. In Fig. 17.23a, a round-nose tool is turning a cylindrical section. Such a tool, with slight modification, is suitable for both roughing and finishing. This tool normally leaves a radius in corners so a separate operation is necessary to remove the radius if a sharp corner is called for on the drawing. But, as sharp corners cause stress concentrations, they should be avoided wherever possible. When a sleeve must go right up to a shoulder on a piece of work, its inner edge can be chamfered to clear the corner radius of the work or the work may be slightly undercut as shown in Fig. 17.23g.

Surfaces perpendicular to the axis of rotation are commonly faced as shown in Fig. 17.23b. The cutting edge is set at a slight angle to the direction of tool travel. Feeding the tool radially outward leaves a plane surface.

Fig. 17.23c illustrates a finish turning arrangement that is quite rapid and entirely suitable for rigid work, particularly in cast iron. The slightly crowned edge of the tool is lined up accurately with the direction of feed. Taking a light cut, the tool is fed longitudinally at each revolution a distance nearly equal to the width of the cutting edge. This leaves a broad ribbonlike tool mark, which is quite satisfactory.

A method of cutting off a piece of work is illustrated in Fig. 17.23d. Holes may be drilled from the solid with drills held in the tailstock

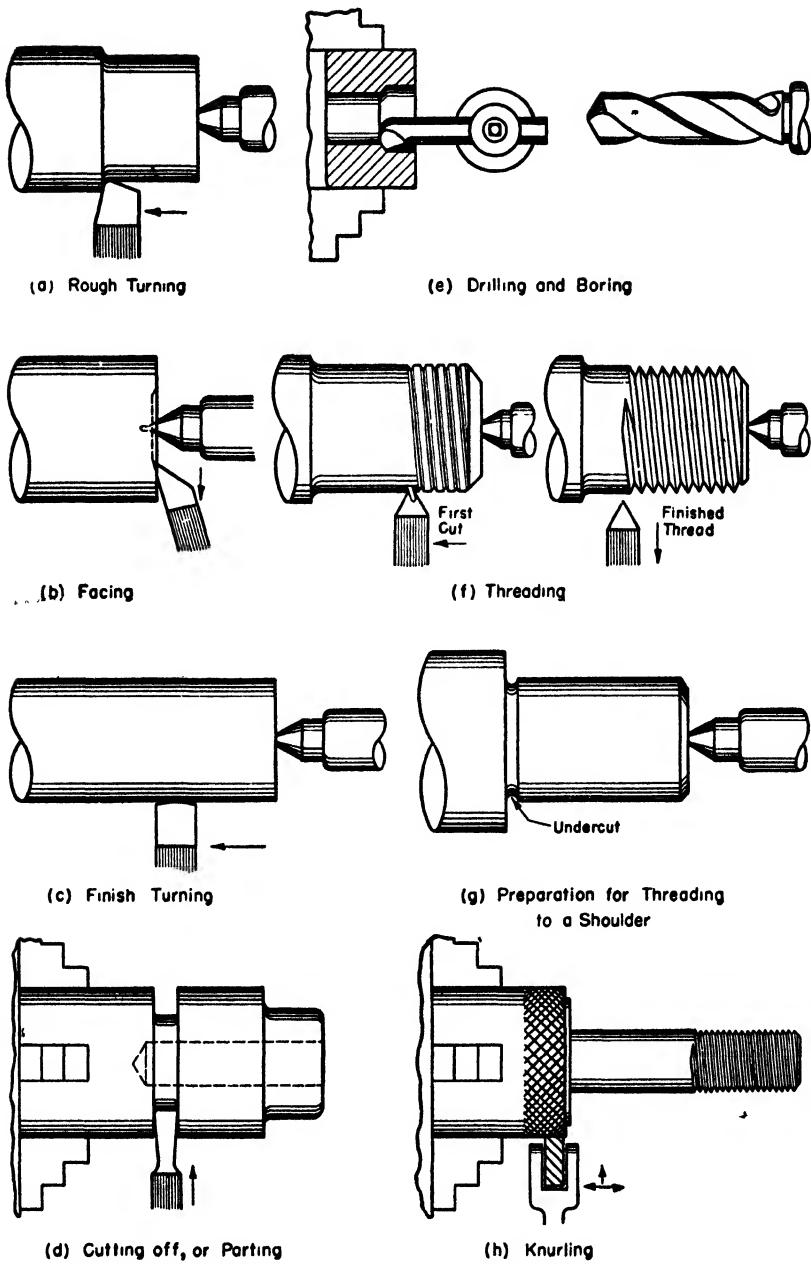


FIG. 17.23. Typical lathe operations.

where the dead center is normally located. Fig. 17.23e shows a drill in the retracted position while a boring tool enlarges the drilled hole. Drilling previous to boring is unnecessary where the hole is cored to a diameter of 1 in. or more.

Threading with a single point tool is accomplished by advancing the tool a distance equal to the lead of the thread at every revolution of the work (Fig. 17.23f). A number of cuts must be taken. It is practically impossible to obtain a complete thread right up to a shoulder, so the design should permit an undercut such as shown in Fig. 17.23g, into which the tool may run at the end of its cut. The same principle applies to internal threads. For threading small holes, a machine tap held in the tailstock is usually used.

External threads may also be produced by use of a threading die. This tool cuts much more rapidly than the single point tool and is generally quite satisfactory, although not so accurate nor so well adapted to cutting very coarse threads as the latter. The die is held in the tailstock of the lathe while the work is rotated. The end of the work to be threaded should be chamfered to provide for easy starting and centering of the die. Thread milling and thread guiding are also used.

The die consists of several cutting blades, which in small sizes are integral with the body. The cutting blades of dies larger than  $\frac{1}{2}$  in. are set in a supporting body (Fig. 17.24) so that they can be removed for grinding. The ends of the blades are chamfered and their cutting action is comparable to the cutting action of the chamfered blades of a tap. This chamfer extends for a distance of two or three threads as for a tap. Where it is necessary to machine threads close to a shoulder, a special die which is chamfered for a distance of only one-half thread can be used as a second operation. As the use of these special dies is expensive, it is much better to provide an undercut two or three threads wide at a shoulder to allow for runout of the chamfered portion of the standard die. When calling for an external thread:

- a. Use a standard thread.
- b. Provide a chamfer where threads start so that the die may take hold easily.
- c. Allow for several incomplete threads at the end, or provide an undercut.

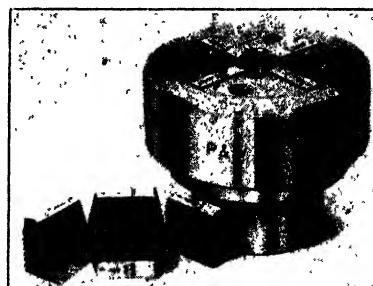


FIG. 17.24. Threading die. (*Courtesy Pratt & Whitney.*)

- d.* Consider other methods of manufacture available. For certain classes of repetitive work, threads may be very inexpensively - cold rolled.

Conical surfaces may be produced in two ways. For comparatively long tapers, the tool is guided by a taper attachment slide on the back of the lathe which is set at an angle to the line of centers. For short tapers the compound rest is used. This is an auxiliary slide on the tool post carriage, which may be swung around to any angle with the axis of rotation. Only hand feed is available for this slide and the amount of its travel is limited.

A knurl is not a cutting tool but is used so generally in connection with machining that it deserves some mention here. Fig. 17.23*h* illustrates a typical knurling operation. When the knurl is pressed against the work, the teeth, cut in the periphery of the knurl, wedge corresponding impressions in the surface of the work. Since this is an operation of displacing rather than removing metal, the knurled diameter will be slightly greater than the original diameter.

In addition to the general points on machining previously listed, the following design points should be observed:

- a.* Be sure all surfaces can be reached for machining with standard tools.
- b.* Avoid sharp corners at shoulders.
- c.* Avoid internal undercuts.
- d.* In general, use threads milled, ground, or cut by dies in preference to those cut by single point tools.

**17.13. Horizontal Universal Turret Lathes.** The horizontal turret lathe is a refinement of the engine lathe. It is capable of duplicating in a much shorter time most parts which can be produced on an engine lathe, although "tooling-up" time is much longer. It is essentially a production machine. The distinguishing feature is a turret, having six separate tool positions, which replaces the tailstock of the ordinary lathe. The turret can be indexed to bring tools such as drills, reamers, turning tools, taps, and dies into use separately without changing the position of the work. A typical setup is shown in Fig. 17.25. Turrets are mounted on either a ram or saddle and may have automatic or hand feed. In the ram type machine the turret is mounted on a slide ram which moves back and forth on a saddle clamped to the lathe bed. In the saddle type the turret is mounted directly on the saddle which moves back and forth in the lathe bed. The ram is the lighter type, has a shorter travel, and is best adapted to bar and light work. The saddle

type is usually built much heavier, offers more rigid support to the tools, and has a longer stroke, making it particularly adapted to heavy chucking work. In both types, the carriage has power control for cross and longitudinal feeds, and may be used for forming, facing, and cutting off at the same time that a turret tool is turning, threading, etc.

Designing for ease and rapidity in mounting the work is particularly important in production applications since each motion eliminated, each second saved, is multiplied many times. Nonsymmetrical work can be rapidly chucked in a combination chuck. This chuck is similar to the four-jaw independent chuck in which each jaw may be moved



FIG. 17.25. Horizontal turret lathe. Note the box tools and threading tools mounted on the turret. A thread gage has been run onto the finished workpiece for inspection purposes. The work is held in a spring collet. (*Courtesy Grisholt Machine Co.*)

independently but has an additional adjustment, like the universal chuck, for moving all jaws simultaneously.

When this machine is equipped for holding bar stock or tubing which can be fed forward to a stop, machined, and cut off, it is commonly referred to as a "hand screw machine."

A standard tool for turret lathe work is the box tool (Fig. 17.26), used for turning uniform diameters. It consists of a cutting bit mounted in a frame with rollers mounted opposite the cutting edge to prevent deflection of the work. The bit and rollers are adjustable to a wide range of diameters.

For turning special contours, a form tool is used. Fig. 17.27 illus-

trates one type of single point form tool used with turret lathes but more generally used on automatic screw machines. This tool is rigidly supported at its center so that its axis is parallel to the axis of the material. It is fed into the work in a direction perpendicular to its axis, and thus turns a surface corresponding to the contour of the cutting edge.

The tool shown has four separate cutting edges, each of which is used in turn as the previous edge becomes dull. When all four edges are dull, this tool is ground on the cutting faces only, so that the contour is maintained.

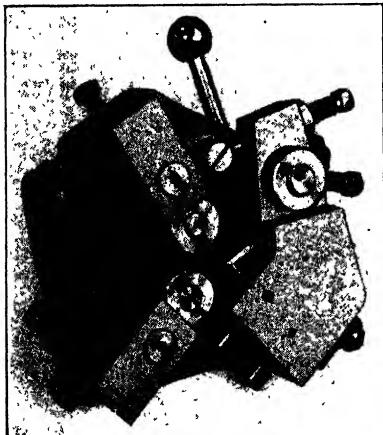


FIG. 17.26. Box tool. (*Courtesy Jones & Lamson Machine Co.*)

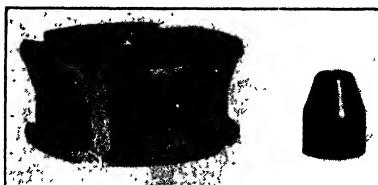


FIG. 17.27. Circular form tool and machined part.

The circular shape provides for a number of such regrinds. Rectangular lathe tools may also have their cutting edges ground to desired contours to make form tools.

The maximum useful width of a form tool will vary with the material to be cut and the accuracy required. The limit in width is generally considered to be  $2\frac{1}{2}$  times the smallest diameter of the work.

**17.14. Automatic Machines.** Perhaps the earliest automatic machine was the automatic screw machine. It is essentially a turret lathe fitted for automatic feed of the stock and for automatic indexing and feed of the cutting tools. Machines of this type handle bar stock of round, hexagon, square, and sometimes nonsymmetrical cross-sections using spring collet chucking. Fig. 17.28 shows one type of automatic screw machine with the turret axis parallel to the single spindle.

Another type of automatic screw machine is the multi-spindle automatic, which may have up to six spindles, instead of one, with cutting operations going on at each spindle simultaneously. Although producing work faster, these machines are more expensive and take more tooling-up time than the single spindle machines. Thus for economical

production, the minimum number of pieces to be machined will be higher than for the single spindle machines.

In addition to the automatic screw machines, there are many semi-automatic machines in which the work is chucked by hand, the rest of the operations being performed automatically. Fig. 17.29 shows a machine of this type in which six vertical work-holding spindles are indexed from one tool position to another during production.

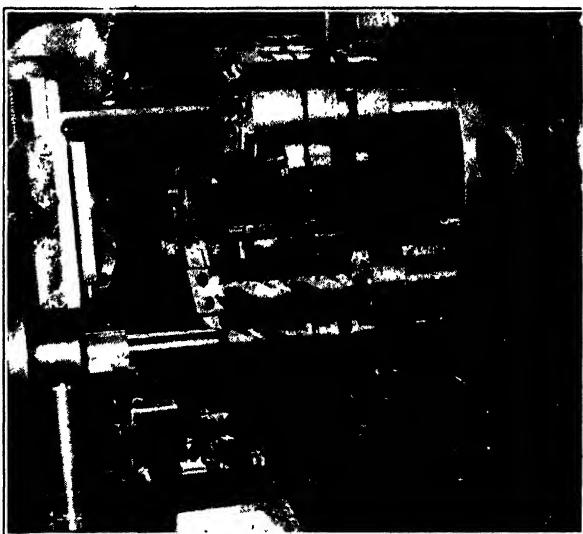


FIG. 17.28. Automatic screw machine. This machine is set up for turning, drilling, and threading operations. A finished piece is shown in the lower left corner. (*Courtesy North American Aviation, Inc.*)

In general, automatic machines are confined to large quantity production since setup time is long and any special tools required are expensive.

In designing work to be done on automatic and semi-automatic turning machines such as described above, the general principles of design as applied to lathe turning should be followed. Particular attention should be paid to finishes and tolerances specified. Wherever possible, the finish left by the cutting tool in an ordinary cut should be designated. Unnecessarily close tolerances should be avoided. A fine finish or a close tolerance means taking a light cut with slow feed and high speed which adds both to setup and machining time. Very fine finishes are obtained by grinding, which requires transferring the work to a different machine. Square shoulders and sharp corners should be avoided and

fillets or undercuts provided instead. It is worth a little time to investigate the cutting tools available and to avoid designs requiring special tools. Generally more material is wasted making parts on automatic screw machines than by some other methods. This is justified by the higher production speed, but the smallest size of available stock consistent with good practice should be used. Cold rolled or drawn stock should be used in preference to hot rolled, where other factors do not enter into the choice, since the scale of the hot rolled stock is very abrasive and causes collets and tools to wear out rapidly.

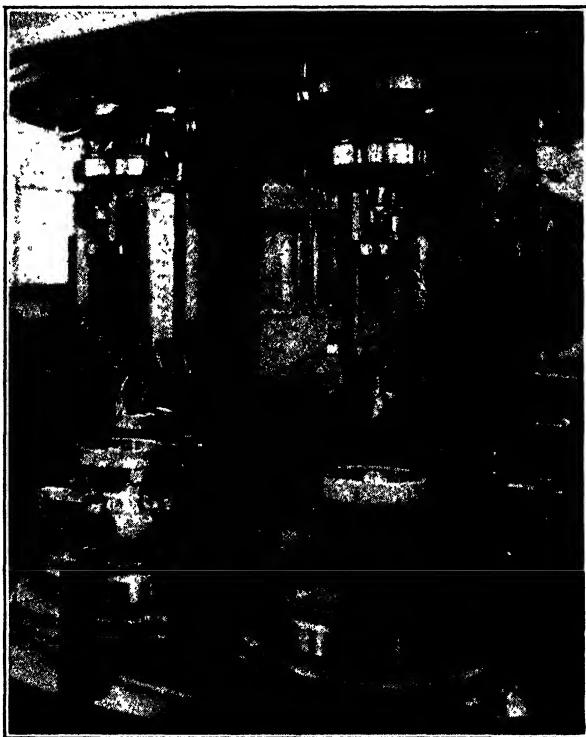


FIG. 17.29. Bullard Mult-Au-Matic.

**17.15. Vertical Turret Lathe.** The vertical turret lathe is similar in principle to a horizontal turret lathe but is designed to handle heavier and larger work than the latter. It is used to bore, turn, or face work which is held at one end only, but it is not adapted to handle bar stock. Fig. 17.30 illustrates a typical vertical turret lathe. It consists primarily of a horizontal circular table mounted on a base, a crossrail which supports the main turret tool holder mounted on a column, and a side rail

which supports a side turret tool holder also mounted on the same column. The main turret, which may hold six separate tools, and the side turret, which may hold four separate tools, are each provided with independent horizontal and vertical power feeds. The main turret head may be swiveled to provide for taper work.

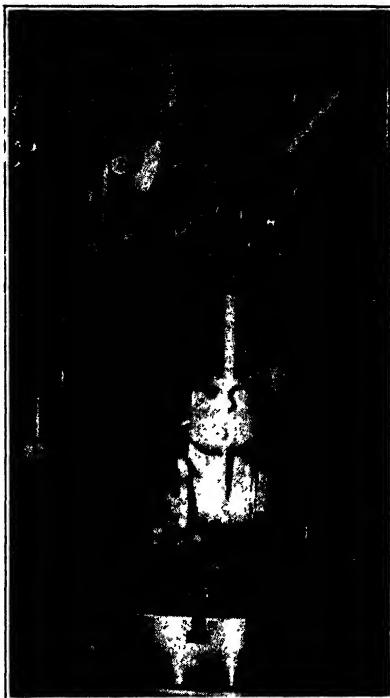


FIG. 17.30. Vertical turret lathe. (*Courtesy Bullard Co. and Machinery Magazine.*)

The revolving table can be equipped with adjustable jaws for chucking the work, and also has T-slots for bolting or clamping the work.

**17.16. Vertical Boring Mill.** For convenience in handling and holding heavy work that is to be turned, faced, or bored, a vertical boring mill (Fig. 17.31) is used instead of a lathe. This machine is most useful for machining parts whose length, or height (as machined), is less than the diameter.

The work is held on the revolving table by clamps or chuck jaws. Cutting tools similar to those used on the lathe are held on the ends of the two rams, each of which may be independently fed horizontally or vertically. Either ram may be swiveled from the vertical so as to bore or turn conical surfaces.

Plates, turbine bucket wheel forgings, and similar flat work are usually held in chuck jaws bolted to the table. A cylindrical hole in the center of the table and an accurate plug may be used to help center work which

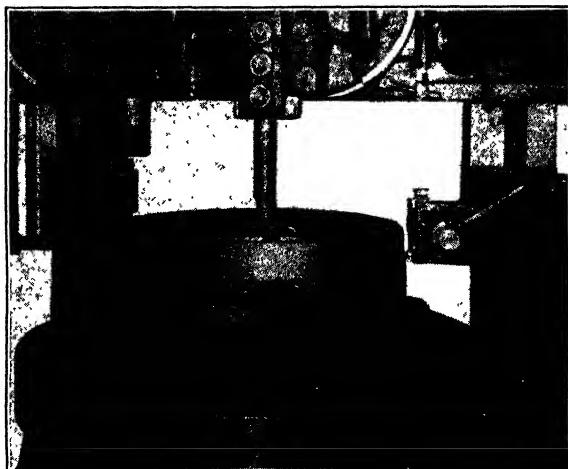


FIG. 17.31. Vertical boring mill.

has a finished bore. The plug is turned at one end to fit the hole in the table. Such plugs are especially useful where work must be turned

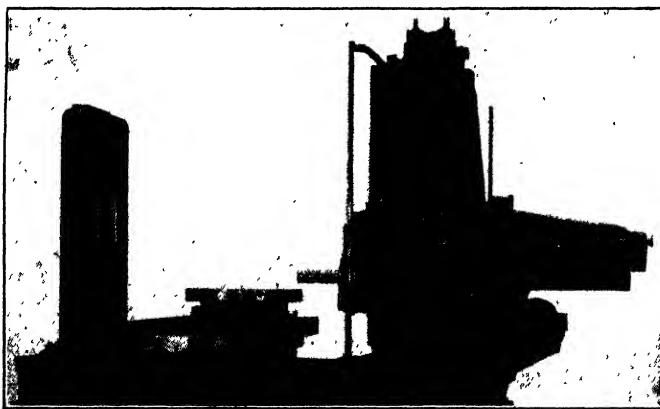


FIG. 17.32. Horizontal boring machine. (*Courtesy Ohio Machine Tool Co.*)

over or transferred from one mill to another. Bored or turned rings may be used in a similar manner. Parts which extend some distance above the table may require braces in addition to the table anchorage.

Such braces may be straight up from the table or may consist of angle plates to which the work is bolted.

**17.17. Horizontal Boring, Drilling, and Milling Machine.** This machine is a general purpose machine tool used for boring, drilling, and milling operations on large or bulky work. It is particularly adapted to work requiring an interrelation of the above operations.

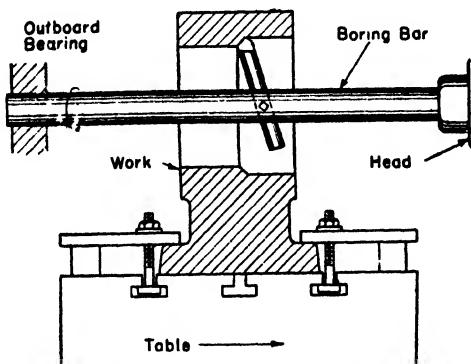


FIG. 17.33. Boring on a horizontal boring machine.

Machines may be provided with one or two horizontal spindles which are adjustable vertically and horizontally, perpendicular to the spindle. The work is clamped to a horizontal table which has longitudinal feed and transverse adjustments, or feed, in the ways of the machine. An outboard bearing is provided to support a long boring bar. This machine may also be equipped for precision positioning of the work with respect to the cutting tool. Fig. 17.32 shows a machine of this type. A setup for boring is illustrated in Fig. 17.33.

**17.18. Milling. Milling Cutters.** In contrast to lathe work, where the excess material is removed by feeding a single point tool into the revolving work, milling is done by feeding the work against a revolving tool, which has a number of cutting edges or teeth. The cutting tools have a variety of forms; only a few of these will be described.

The plain milling cutter (Fig. 17.34A) is used for machining flat surfaces. It cuts on the periphery only.

The end milling cutter (Fig. 17.34B) can cut on the periphery or the end, although it cannot be sunk endwise into solid metal since it has no cutting edges at the very center. Being supported and driven from one end by a tapered shank, it can reach surfaces that could not be reached with a plain milling cutter. Fig. 17.35c shows an end mill machining a flat spot on a sloping surface preparatory to drilling.

The side milling cutter (Fig. 17.34D) can cut not only on its periphery

but on both sides as well. It is used for milling keyways and grooves. The staggered-tooth construction facilitates the cutting action. When a keyway is cut with a side milling cutter (Fig. 17.35a), a radius equal to that of the cutter is left at the end of the cut. If this radius is objectionable, a second operation with an end mill of a diameter equal to the keyway width is used to clean out the end to the shape shown in Fig. 17.35b.

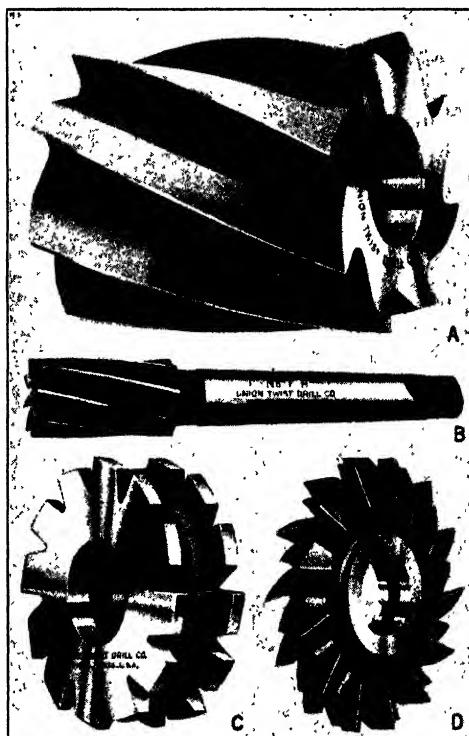


FIG. 17.34. Milling cutters. (*Courtesy Union Twist Drill Co.*)

- |                          |                         |
|--------------------------|-------------------------|
| A. Plain milling cutter. | C. Form milling cutter. |
| B. End milling cutter.   | D. Side milling cutter. |

When the surface to be milled has a curved or special cross-section, a form cutter must be used. Fig. 17.34C shows a cutter of this type. Special contours may be obtained by various combinations of standard and special cutters as shown in Fig. 17.36.

*Types of Milling Machines.* Fig. 17.37 and 17.39 show two of the principal types of milling machines for general purpose work. In the universal milling machine (Fig. 17.37), the cutter spindle is horizontal

and is provided with a tapered hole for receiving arbors on which the cutters are mounted. An outboard bearing is provided for long arbors. The work table can be fed vertically, longitudinally, and transversely,

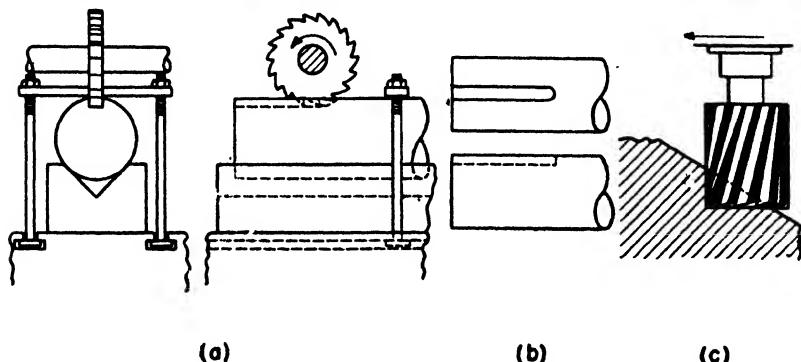


FIG. 17.35. Milling operations.

and is also capable of being swiveled in a horizontal plane. This latter feature permits spirals to be milled on a universal machine, as will be

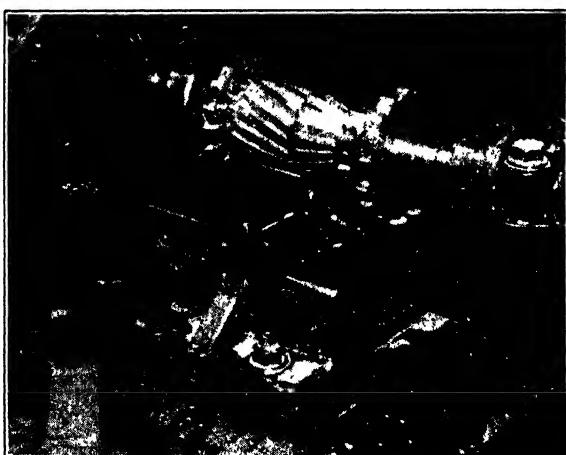


FIG. 17.36. Standard and special milling cutters used in combination to produce a gun contour. Gun blank, after milling operation, is shown in lower left corner. (Courtesy Colt's Patent Fire Arms Manufacturing Co.)

explained later. In Fig. 17.38 a universal miller is shown set up with special form cutters for a milling operation on gun parts.

The vertical spindle milling machine (Fig. 17.39) is similar to the universal except that the spindle is vertical and the table is not swiveled.

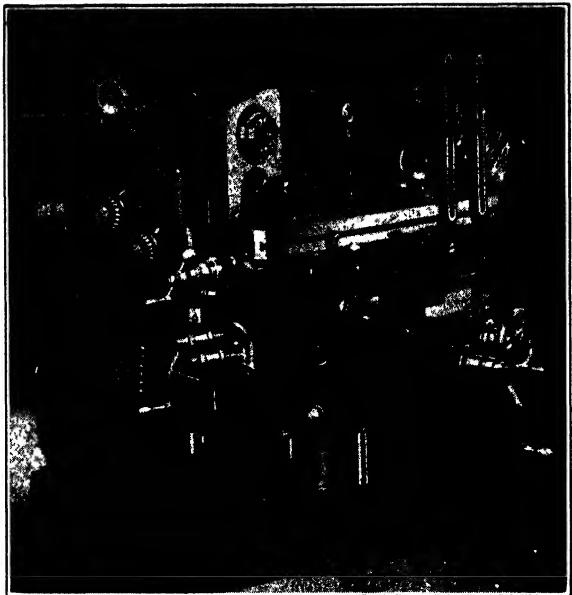


FIG. 17.37. Universal milling machine. (*Courtesy Cincinnati Milling Machine Co.*)

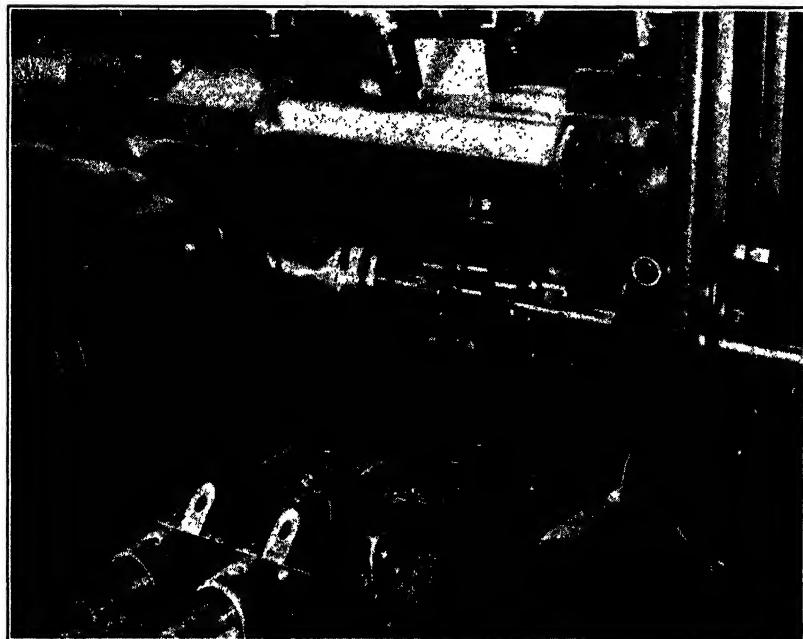


FIG. 17.38. Universal milling machine operation. Form milling cutters are mounted on an arbor which is supported by the outboard bearing. (*Courtesy Colt's Patent Fire Arms Manufacturing Co.*)

It is particularly adapted to end or face milling of horizontal surfaces, to profiling, etc.

The thread milling machine is a special application milling machine. It is used for quantity production of accurate external or internal threads in the coarser pitches. Threads or worms are cut with a form cutter having single or multiple threads. As in other types of threading, design must provide undercuts for runout of the cutter. Mounting is done in chucks, collets, or between centers.

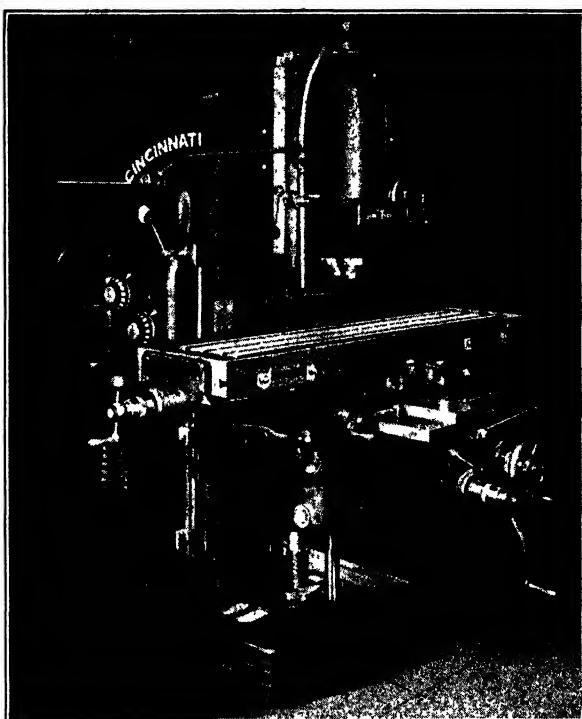


FIG. 17.39. Vertical milling machine. (*Courtesy Cincinnati Milling Machine Co.*)

*Milling Operations.* Work may be held for milling (a) by clamping directly to the table, (b) in a machine vise, (c) in a fixture, or (d) on the dividing head or between it and a center. The first three have been encountered before but the fourth is peculiar to the milling machine and will bear some explanation.

As its name implies, the dividing head (Fig. 17.40) is a device for dividing a circle into a number of equal divisions. The work is connected to the dividing head work spindle and successively positioned for

each cut by rotating the dividing head spindle the required fraction of a turn by means of a worm wheel mechanism. The dividing head finds application in cutting gears, flutes, graduations, and similar work.

For work that must be held between centers, a tailstock is provided for supporting the other end. The dividing head spindle motion is then transmitted to the work through a dog.

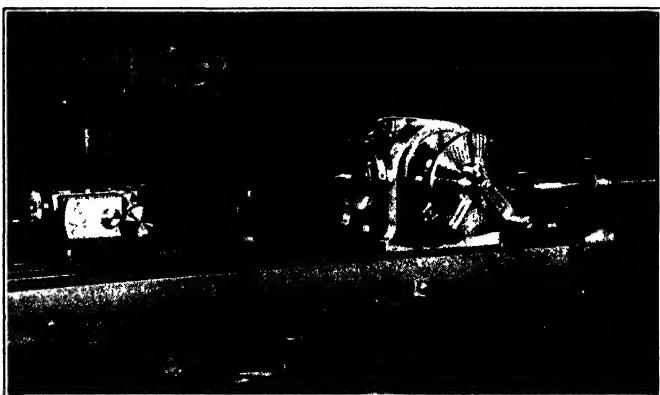


FIG. 17.40. Dividing head. (*Courtesy Cincinnati Milling Machine Co.*)

Spiral milling is accomplished by swiveling the universal milling machine table to the required helix angle, then gearing the dividing head mechanism to the table feed in such a way that the required combination of rotary and axial motion is imparted to the work.

In designing for milling:

- a. Design for standard size milling cutters.
- b. Avoid milled surfaces closer to a wall than necessary. These call for small diameter cutters which slow the cutting operation.

**17.19. Planing.** The planer is a general purpose machine tool designed to rough and finish machine a plane surface by driving the work in a horizontal straight line against a stationary single point cutting tool which may be fed, between cuts, vertically or horizontally at right angles to the direction of the drive.

The work is clamped or bolted directly to the machine table, which has a straight-line reciprocating movement only, with no vertical or cross adjustment. The tools are similar to those used on the engine lathe.

Planers are of two general types, the open side and the double housing.

An open-side planer is illustrated in Fig. 17.41. Each of the two vertical tool heads may be swiveled, and each is provided with self-contained vertical feed and with horizontal feed along the crossrail. The cross-rail is adjustable vertically. The side tool head is provided with a self-contained horizontal feed and is adjustable vertically on the housing. The double-housing planer is essentially the same in construction and operation as the open-side type, but in addition has another housing on the opposite side of the bed which functions as an additional support for the crossrail.

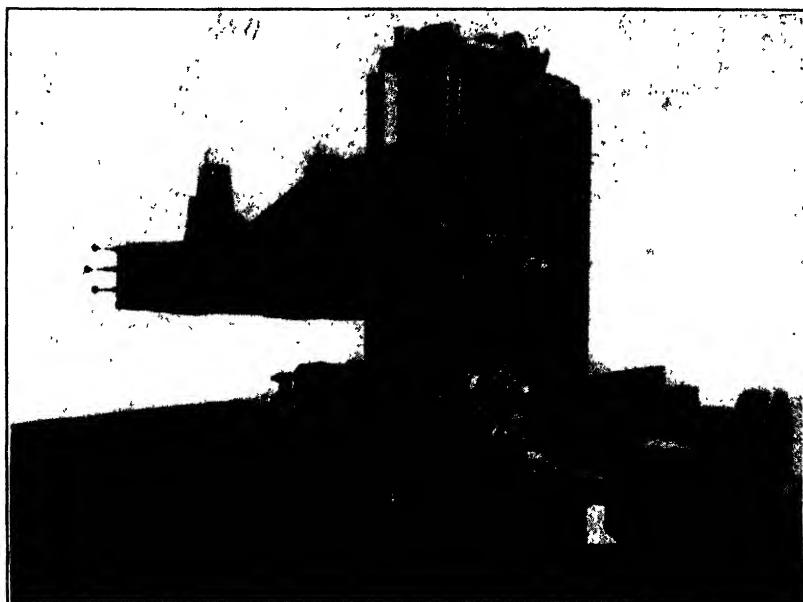


FIG. 17.41. Open-side planer. (*Courtesy G. A. Gray Co.*)

A planer is used to machine accurate plane surfaces; however, it may be used also to cut grooves and keyways and may be set up to machine certain curved and warped surfaces.

Since the mechanism for reversing the table is not always absolutely positive, the point of reversal may vary slightly. Hence, the engineer should provide a reasonable run-out space for the tool at each end of the surface to be finished.

**17.20. Shaping.** The shaper is used to produce the same type of surface as the planer but is adapted to handle smaller and lighter work. The essential difference between the planer and the shaper is that in the latter the work is held stationary and the cutting tool is driven against it.

Figure 17.42 illustrates a universal shaper, which is a general purpose machine tool. The cutting tool is supported in a swivel head which is carried by a ram having a horizontal reciprocating motion. The work is held in a vise or clamped directly to a rectangular table. The table is fed between strokes in a direction at right angles to the stroke of the ram. Vertical feed is accomplished by a vertical movement of the tool in the head. While the ram reversal is positive in this machine, some tool clearance must be provided at each end of the cut to permit the chip to be detached and to let the tool get into position for the next stroke.

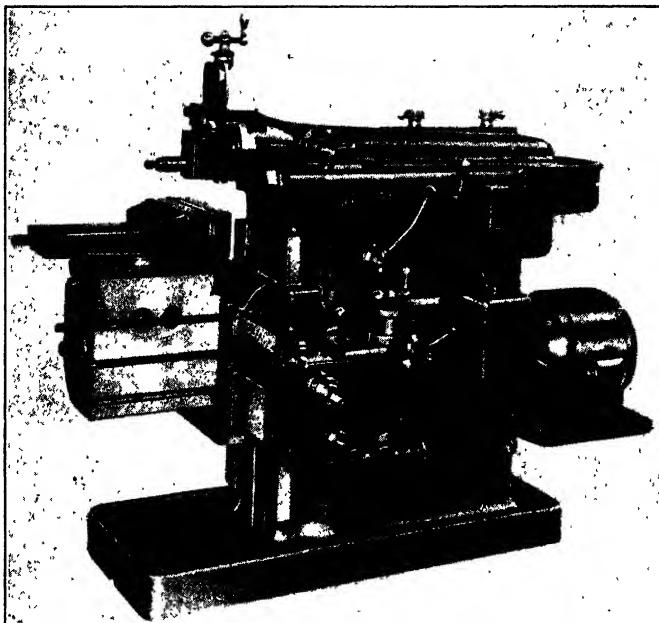


FIG. 17.42. Shaper. (Courtesy Rockford Machine Tool Co.)

In addition to the horizontal *push-cut* shaper there are the *draw-cut* shaper, used for the same type of work; the *vertical* shaper, used for slotting and keyseating; and special purpose shapers, such as the *gear* shaper, to be mentioned later under gear cutting.

**17.21. Broaching.** A broaching tool resembles a very coarse file and consists of a number of cutting edges set in the main body of the tool. Desired contours are obtained by a gradual change in the shape of each successive cutting edge, beginning with the original shape and ending with a number of teeth having the shape of the contour required. These final teeth serve to produce a very fine finish. Some typical broached holes are shown in Fig. 17.43.

Broaching machines are arranged to either push or pull the broaching tool through or across the surface to be finished. Machining time is only a matter of seconds and is complete in one pass of the broach. Parts to be broached may be clamped in position or allowed to "float" in special jigs or fixtures. Since a number of edges are cutting at once, the broaching forces are much greater than forces of other machining operations.

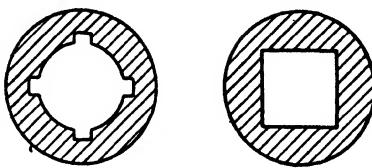


FIG. 17.43. Typical broached holes.

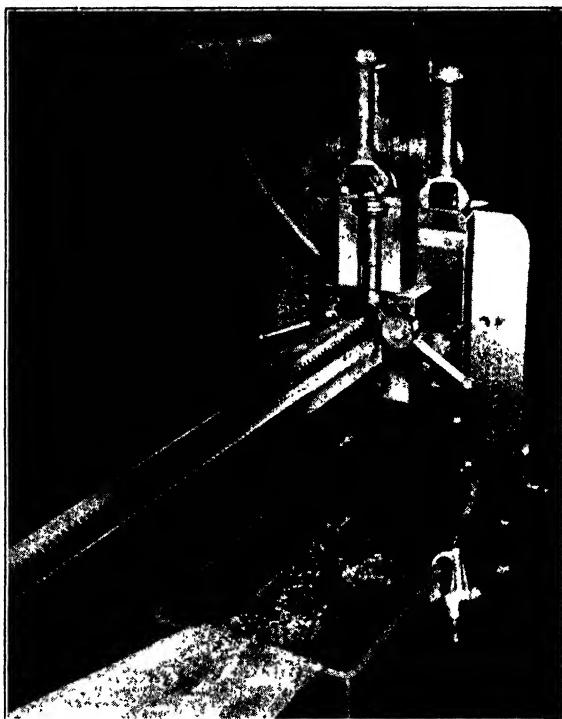


FIG. 17.44. An internal broaching operation. Note the gradual change in the contour of the teeth of the broaching tool. Samples of the work before and after the broaching operation are shown in the upper part of the illustration. (Courtesy LaPointe Machine Tool Co.)

Broaching is particularly adapted to holes (internal broaching) and is coming into extensive use in finishing flat or irregular surfaces (surface broaching). It is generally a high production process, as tools are expensive. A broaching operation is shown in Fig. 17.44.

**17.22. Grinding.** Machine grinding is generally a finishing process. It may be used to finish machine almost any surface which has been previously rough machined by some other method, and also may be used to rough machine the surplus from material which is too hard to machine by other methods. The material is fed against the grinding wheel, which is revolved at sufficient velocity to attain a surface speed of 3000 to 5000 ft per min.

**17.23. Grinding Wheels.** A grinding wheel is made up of many small grit particles held together by a bonding material. It may properly be called a cutting tool with many cutting teeth, since each grit projecting from the face of the wheel cuts a tiny chip resembling the larger chips made by the cutting tools previously described. The two kinds of grit most commonly used are silicon carbide and aluminum oxide, both in a crystalline form. The crystals are crushed and the resultant particles of grit, sorted as to size, are bonded by some material such as clay, glass, rubber, shellac, or phenolic resin. The cutting surface of the wheel may be the periphery, the side, or both the periphery and the side. As the cutting edges of the small grit particles become dull, the cutting forces increase and pull these dull particles from the bonding material. This exposes new sharp grit particles and is the natural wear of the wheel. If the contour of the cutting face of a grinding wheel includes too sharp an angle, the particles of grit at this point are not sufficiently supported and cause rapid wear of the wheel by prematurely pulling out of the bonding material.

There are many cutting edges to share the dulling effect of intermittent cuts, so that the minimum thickness of chip that it is practicable to remove by grinding may be less than the thickness of the surface from which it is removed and must only exceed the thickness of the cutting edge of the grit. Since this edge is extremely thin, it is practicable to machine certain surfaces to a greater degree of accuracy by the use of a grinding wheel than by the use of any other cutting tools. The wheel pressure required to remove minute chips is light and causes comparatively little deflection of the work or the wheel.

**17.24. Grinding Machines.** The more common types of grinding machines are the universal, cylindrical, internal, vertical surface, horizontal surface, and centerless grinders.

*Universal and Cylindrical Grinders.* A universal grinding machine is shown in Fig. 17.45. Work may be mounted between the centers or chucked in the spindle. For cylindrical grinding, the table, on which the spindle and tailstock are mounted, is parallel to the axis of the grinding wheel. For other grinding operations it is possible to swivel the spindle head, feed the grinding wheel horizontally toward the table,

and give the grinding wheel a short reciprocating motion parallel to the table motion. Fig. 17.46 shows a universal grinder set up for finish

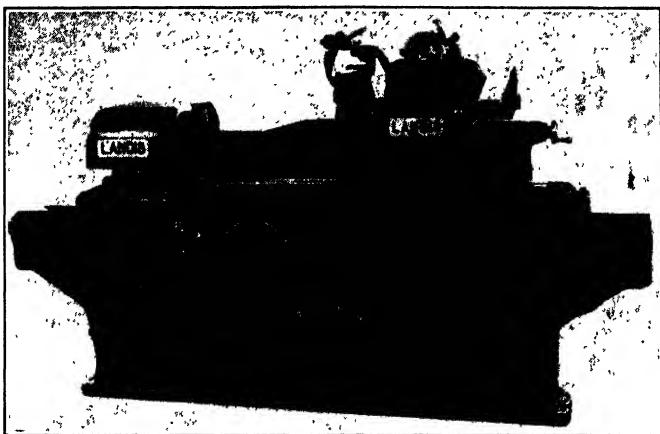


FIG. 17.45. Universal grinder. (*Courtesy Landis Tool Co.*)

grinding a flange diameter. The cylindrical grinder is a production machine confined to grinding straight cylindrical and taper work.

*Internal Grinder.* The internal grinder (Fig. 17.47) is used to finish internal surfaces such as engine cylinders, ball bearing races, and similar work which requires extreme accuracy and high finish. The work is revolved against the grinding wheel in an opposite direction and at a much slower speed than the speed of the wheel. The wheel must be smaller in diameter than the surface to be ground, and when this surface is of small diameter, the revolutions per minute of the wheel must be extremely high in order to produce the necessary surface speed on the periphery of the wheel. A small wheel wears very rapidly, so that the work should be designed with very little stock to be removed by grinding. Adequate wheel clearance should be allowed at the ends of the cut.



FIG. 17.46. Grinding a flange diameter on a Universal grinder. A combination chuck with its jaws reversed is used here to hold the work on an internal diameter. (*Courtesy Landis Tool Co.*)

*Surface Grinders.* A surface grinder is a general purpose machine tool used to finish machine a plane surface. There are two types —

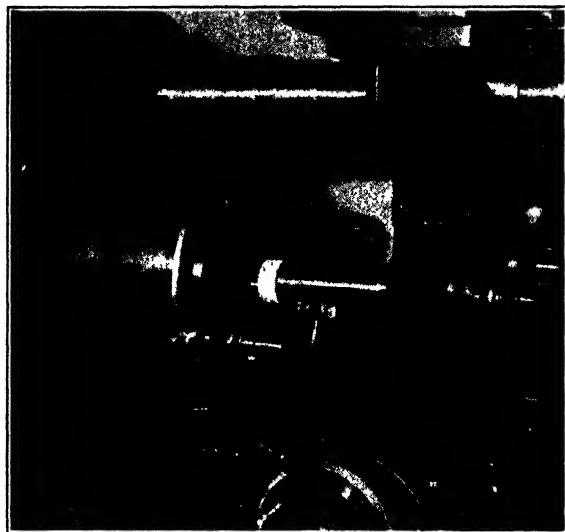


FIG. 17.47. An internal grinding operation.  
(Courtesy Bryant Chucking Grinder Co.)

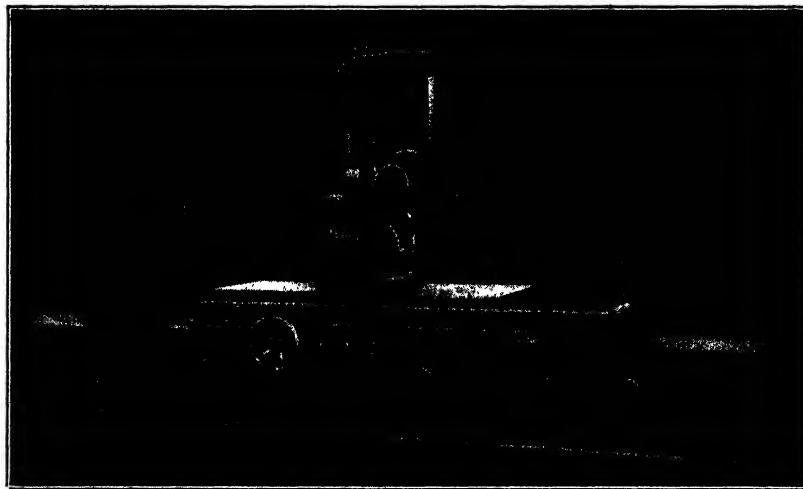


FIG. 17.48. Horizontal surface grinder. (Courtesy Machinery Magazine.)

the horizontal and the vertical. In the horizontal type the axis of the grinding wheel is horizontal and grinding is done on its periphery. In

the vertical type the axis of the grinding wheel is vertical and grinding is done on its bottom face.

Both types of grinders may have either a reciprocating table or a revolving table. Magnetic material may be held to these tables by magnetic chucks. Nonmagnetic material is clamped or bolted to the tables. Surface grinders with rotary tables are particularly adapted to grinding a number of like small pieces simultaneously. A horizontal surface grinder with a reciprocating work table is shown in Fig. 17.48.

*Centerless Grinder.* The centerless grinder is a repetitive machine tool used to produce a fine and accurate finish on cylindrical, conical, and spherical surfaces, such as piston pins, roller and ball bearings, taper pins, and small shafts. It is by far the most economical method of producing such surfaces if the quantities are such as to justify the setup.

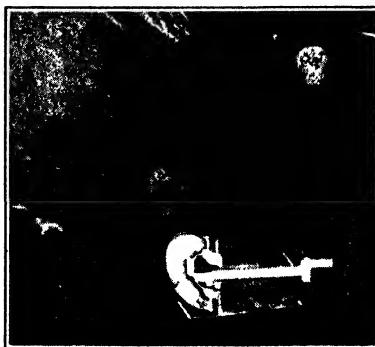


FIG. 17.50. A centerless grinding operation. The cylindrical portion of a compressor shaft is being finish ground. A "GO, NO-GO" gage is shown in position for inspection on the finished piece in the foreground.

with a rough surface, and emerging from the other side with an accurately finished surface.

The in-feed method of grinding is used to grind cylindrical parts which have interfering shoulders and conical or formed surfaces. The work is placed upon the work support, and the latter, together with the

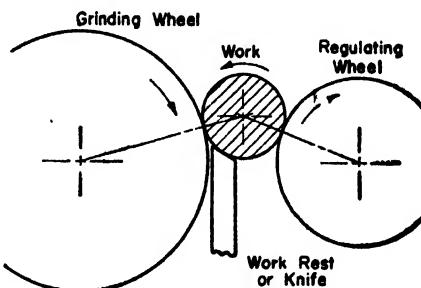


FIG. 17.49. Centerless grinding.

The principal elements of this machine are the grinding wheel, regulating wheel, and the work rest (see Fig. 17.49). These three elements, properly located with respect to each other, serve to support and guide the work while it is being ground, no other support or guide being necessary. The regulating wheel controls the rotational speed of the work and the rate of feed.

The through-feed method is used to grind cylindrical parts which have no interfering shoulders. The work is passed between the wheels from one side of the machine, entering

regulating wheel, is fed forward, forcing the work against the grinding wheel. The grinding wheel has its periphery shaped to the profile desired in the work. Fig. 17.50 shows an operation of this type.

**Thread Grinding.** Great progress has been made recently in the grinding of threads. A wheel dressed to the thread profile is fed along the work like a single point threading tool in a lathe. Grinding may be used both for roughing and finishing threads. It is most commonly used for grinding threads in hardened material.

**17.25. Design for Grinding.** When designing for parts that are to be ground:

- a. Provide working space for the grinding wheel.
- b. Avoid necessity for sharp angles on the cutting face of the wheel, i.e., avoid sharp radii in the corners of the work.
- c. Do not require a cylindrical wheel to grind on its side at the end of a diameter of the work; provide an undercut.
- d. Avoid internal grinding of small, deep holes; if such holes are necessary, be sure to provide a recess at the bottom into which the wheel may run at the end of the stroke.
- e. Avoid narrow slots which must be ground on the sides.
- f. Do not require accurate radii for ground fillets.
- g. All cold worked metals contain internal stresses, and if some of the surface is removed, the part will warp. For that reason, accurate dimensions should not be expected if cold worked metal is not stress-relieved before grinding.

**17.26. Honing and Lapping.** Machining to produce finer surfaces than those obtained by grinding is accomplished by honing or lapping.

Honing is done with sticks of fine bonded abrasive material. The honing machines apply several sticks to the work simultaneously. Honing of internal bores is accomplished by spring mounting the bonded sticks on the periphery of a cylindrical body. This composite tool is reciprocated the full length of the bore and given a twisting motion during the stroke, producing a crisscross surface pattern. Surfaces are sometimes hand finished, using single honing sticks applied manually. Honing is used in finishing internal combustion engine cylinders, gun bores, bearings, etc.

In lapping, a fine abrasive carried in an oil medium is applied to a work surface by the reciprocating motion of a *lap* of soft or porous metal such as cast iron or lead. The laps have various shapes according to the surface to be finished. Lapping produces a very fine finish and is used for correcting small surface imperfections, for producing close fits between contact surfaces, and for finishing gears.

**17.27. Gear Cutting.** The principal methods of cutting gears are milling, shaping, and hobbing.

In the milling process, gear blanks are mounted on mandrels or in

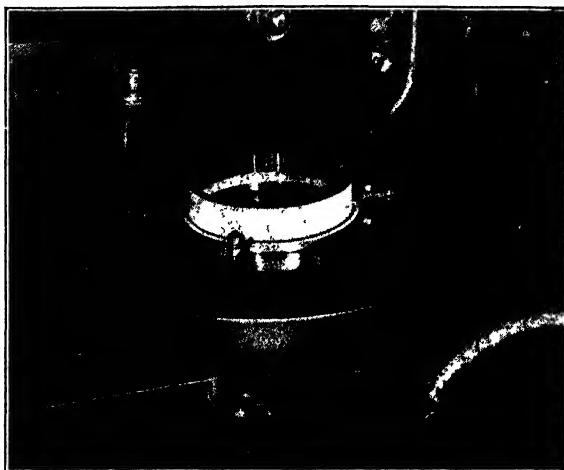


FIG. 17.51. A gear shaper operation. (*Courtesy Machinery Magazine.*)

chucks attached to the dividing head. One tooth is cut at a time with a form cutter whose contour conforms to the gap between two teeth. The blank is indexed to the successive tooth positions for similar cuts until the gear is completed.

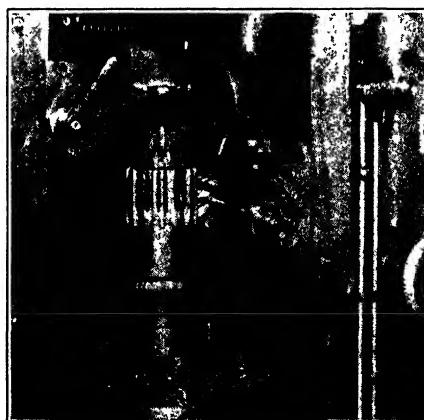


FIG. 17.52. A gear hobbing operation.

The shaper method is shown in Fig. 17.51. The cutter which has a reciprocating motion and the gear blank both revolve as the teeth are

cut. Spiral gears may be cut by giving the cutter a spiral motion during the cut.

Gears are hobbed as shown in Fig. 17.52, using a cutter of the type illustrated in Fig. 17.53. In operation the hob is rotated and fed across a gear blank. The teeth in the hob cut the gear blank until the hob finally meshes with the gear like a worm and worm gear.

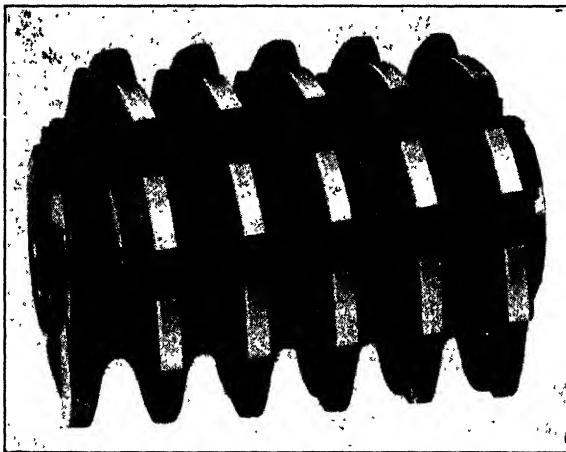


FIG. 17.53. Hob-cutter. (*Courtesy Union Twist Drill Co.*)

For high production of small internal gears, broaching is both rapid and accurate although tools are expensive. Gears of very hard material are ground.

Gear blanks are mounted in spring collets, in chucks, on threaded or expanding arbors, between centers, or clamped to a face plate during the cutting operations. In designing gears remember:

- a. Leave plenty of stock beneath the teeth. Removing the metal between the teeth sometimes removes stressed material, and gears with little material between bore and teeth are apt to warp.
- b. Be consistent in specifications. Machining of the gear blank and cutting of the gear teeth are not ordinarily done by the same operator or department. If the gear teeth are to be concentric with an inside bore and the gear is to be chucked on an outside diameter, be sure to specify concentricity of the outer diameter and inner bore. If the gear teeth are to have a limit on the lateral runout (lateral surface deviation from a plane normal to the axis), specify a limit for lateral runout

on the machined blank (usually specified on 1 in. radius circle). The gears can be no more accurate than the blanks they are made from and no more concentric than the arbor on which they are cut.

- c. Avoid small bores if gears are to be cut when mounted on an arbor. A larger bore decreases the lateral runout.
- d. Avoid thin gears; they are apt to warp.
- e. Gears of diameter greater than 1 in. can be mounted easily for gear-shaper operation by providing three equally spaced mounting holes about  $\frac{1}{4}$  in. in diameter.
- f. On small gears (less than 1 in. diameter) leave plenty of shaft for mounting and specify that it be cut to desired length after cutting teeth.
- g. Gears for light loads have been satisfactorily die cast. Large gears, where accuracy is not important, can be sand cast. Small thin gears can be stamped successfully.

**17.28. Metal Sawing.** Cutting off bar stock and other material for subsequent machining operations is an important process in production work. Several types of machines are available for this operation.

The power-driven hacksaw is in common use. It consists simply of a metal blade with teeth properly cut for metal cutting and a mechanical or hydraulic means of reciprocating this blade. Stock is fed by hand or can be fed automatically.

The circular saw is also used for cutting-off operations. A circular disk with cutting teeth, usually with cutting bit inserts, is rotated and fed into the work. This operation is commonly known as *cold sawing*.

Very hard metals and plastic rods and tubes may be cut with very thin high-speed abrasive disks. The abrasive is usually bonded with rubber or Resenoid for flexibility.

In addition to cutting-off operations, irregular contours can be cut with a band saw. A very useful machine of this type is equipped with automatic welding equipment for flash-butt welding together the saw band after it has been inserted in a hole for internal contour cutting. The butt weld is ground smooth before cutting and the band is broken at completion of the sawing operation. Filing can also be accomplished on these machines by fastening a series of files to a flexible steel band.

**17.29. Conclusion.** Details of machinery have been purposely avoided in this chapter. There are many good handbooks and textbooks giving complete descriptions and operating instructions for these machines.

Design for machining has been emphasized, but rules of thumb and hints cannot supplant experience and personal contact. Close coopera-

tion between the engineer and machinist is, therefore, very desirable. When designing for a machining operation or process, use another's experience for lack of your own. Consult the factory to find out the following points, and then design accordingly:

- a. What machines are available.
- b. What are the standard cutting tools.
- c. What tolerances can be held.
- d. What material sizes are stocked.
- e. What finish is produced by an operation.
- f. What methods are used to hold the work.

Before deciding upon a machining operation, investigate other possible methods available for producing a part satisfactorily. Many operations such as casting, punching, forging, cold heading, etc., are completely satisfactory and are cheaper both as complete operations and as operations preliminary to machining.

#### REVIEW QUESTIONS

1. How does a finish cut differ from a rough cut in speed of feed and speed of rotation of work?
2. Distinguish between "laying out" and "setting up."
3. Name at least five factors affecting the maximum size of chip that it is practicable to take. What determines the minimum chip size?
4. Name two tools which are classified as single point cutters. Name three classified as multiple point cutters.
5. For what classes of service are the following tool materials usually used?  
(a) High carbon steel. (b) High speed steel. (c) Carboloy. (d) Nonferrous alloys.  
(e) Abrasives.
6. Why is it difficult to drill a hole 0.020 in. in diameter through a piece of steel  $\frac{3}{8}$  in. thick?
7. List the operations necessary in making a flat-bottomed hole. How could you thread this hole within two or three threads distance of the bottom?
8. What must be done to allow a hole to be drilled in a sloping surface?
9. Distinguish between counterbore and countersink.
10. What functions do the following perform: chuck, reamer, mandrel, steady rest, spring collet, dog, and broach?
11. Although used in lathe work, a knurling tool is not, strictly speaking, a cutting tool. Why?
12. List three methods of cutting threads. For what general purpose is each used?
13. What is the main purpose of using oil in machining operations? What other purpose may it serve?
14. How would you turn a hemisphere on the end of a  $\frac{1}{2}$  in. diameter steel rod?
15. What tolerance should you expect if you dimension a steel block only as  $\frac{1}{2}$  in.  $\times \frac{3}{4}$  in.  $\times \frac{5}{16}$  in.?
16. What is a lapped surface and how may it be made?
17. If a shaft containing a shoulder is to be surface ground, what design precautions should be observed?

## CHAPTER XVIII

### GAGING, INSPECTION, AND QUALITY CONTROL

#### GAGING AND INSPECTION

By C. H. BORNEMAN

**18.1. Introduction.** Before the advent of mass production methods in American industry, products were produced largely by job-shop work.<sup>1</sup> Each of the mating parts of a machine or mechanism were selectively hand fitted to each other and seldom would they fit the similar parts of another machine of the same design. The hand fitting involved was expensive, selling prices were high, and the quantities of machines of a single design produced were necessarily low.

The fundamental basis of mass production is careful control of the dimensions of parts and of the processes used so as to obtain uniformity of parts, thus making them interchangeable between different assemblies of the product. This idea of interchangeability of parts is thought to have originated with Eli Whitney, the famous inventor of the cotton gin. Whitney conceived the idea when he was called upon by the Government to speed up production of rifles during the War of 1812. Through interchangeable manufacture it is possible to select at random from a large number of parts each part to be assembled in a product. Consequently, savings in time and expense result from elimination of hand fitting, except for very special close working parts. Even in modern job-shop work where small quantities are involved, parts are usually made accurately so that interchangeable replacement parts may be reproduced later if that is necessary. But with either high or low production, the cost of obtaining uniformity for interchangeability and proper functioning must always be offset by a reduction in the cost of assembly and of servicing the product.

The production of parts of close dimensional accuracy necessarily requires good tooling and processing and good measuring and indicating devices. The latter are known as gages. In the job-shop work, the cost of special gages for a single job is seldom justified, so standard general purpose gages such as micrometers and vernier calipers are most often used. High production work, where interchangeability without resort to selective grading and assembly of parts is usually most

<sup>1</sup> A job shop is one that specializes in manufacturing products in small quantities and to special design.

economical, often justifies elaborate gages. Some of these special purpose gages and the more common standard gages will be briefly described in this chapter. Before this is done, however, some aspects of manufacturing tolerances will be considered.

**18.2. Tolerances, Limits, and Allowances.** Since it is not possible to produce or measure parts to absolute accuracy, it is necessary that some variation from prescribed dimensions be permitted. The total permitted variation in a particular dimension of a single part is termed the *tolerance*. When a designer specifies a shaft length as 1.5 in., for example, he is indicating a nominal size and it is understood between him and the shop that the accuracy of this dimension is to be in accordance with established practice. Shop-run tolerances depend on the type of work done, but for general apparatus manufacture they are usually in the range  $\pm 0.010$  in. to  $\pm \frac{1}{64}$  in. If a greater degree of accuracy is required, the designer specifies this by superscripts denoting the permissible variation. The shaft length might have been dimensioned  $1.500^{+0.002}_{-0.002}$ , which indicates a tolerance of 0.004 in.

According to this specification, the largest and smallest acceptable dimensions are 1.502 in. and 1.498 in. These two dimensions are termed the *limits*. They prescribe the boundary dimensions of the tolerance.

Small tolerances are usually required on a part to assure the proper fit with other parts. Fits are of three general kinds: a clearance fit, a close fit, and an interference fit. For various applications it is necessary to have different amounts of clearance, or interference; therefore each industry subdivides these kinds of fits to suit the classes normally used in their work.<sup>1</sup> The intentional difference in dimensions of mating parts prescribed to secure the correct fit is termed the *allowance*. The tolerances on the fit dimension of each part cause the fit clearance or interference to vary, but the allowance is commonly understood to be the minimum clearance or the maximum interference obtained by mating the largest internal member with the smallest external member. The effect of tolerance on the fit is very important to the engineer and has been considered in the tentative system of allowances and fits set up by the American Standards Association.

When the tolerance for a dimension is applied such that the dimension can vary both plus and minus, the tolerance is called *bilateral*. The dimension  $1.500^{+0.002}_{-0.002}$  used above is an example of a bilateral tolerance. A *unilateral* tolerance is applied in only one direction from the dimension, e.g.,  $1.500^{+0.000}_{-0.004}$ . It is most common in industry

<sup>1</sup> See "Tolerances for Cylindrical Fits," by John Gaillard, American Standards Association.

now because it permits changing the tolerance values without altering the characteristics of respective mating parts.

**18.3. Choice of Tolerances.** In order to give the factory all possible tolerance without detracting from the practical functioning of the product, dimensions affecting assembly of a given part should be related to a strategic subdatum line for that assembled part. For instance, if several flanges with rabbet fits were to be assembled to a large casting or other part, it would be best from the gage and the manufacturing standpoint to locate the centerline of the rabbet fit with proper tolerances from the main datum line (or other reference point), and to dimension the flange bolt holes from the rabbet fit centerline. The rabbet fit centerline would then be a subdatum line. This applies particularly to unit, or small lot production.

This dimensioning method will help the layout man or the tool designer to properly relate the flange bolt holes to the rabbet fit hole. A much wider tolerance may be permissible for the location of the rabbet fit with relation to the main datum line of the product than would be permitted for the relation of the flange bolt holes to the rabbet fit. An exception occurs when it is known that all holes in the product will be produced on a jig borer, or in jigs produced on a jig borer. Holes produced by either of these methods should be dimensioned from the main datum line, thus eliminating recalculation to relate these holes to this line.

In the design of large apparatus, which is usually tailor made and receives the personal attention of the engineering department, a "shop practice" in line with understandings between the factory and the engineering department may result in the elimination of full dimensioning of the product parts. It is well, however, to have these practices covered by definite written or blueprinted instructions so that they do not become too flexible over a period of years, and so that they are not the personal knowledge of a few designers or workmen. The passage of these individuals or a move of the work to another plant can result in embarrassing manufacturing delays and field complaints.

Tolerances for location of a number of holes should be the same in both coordinate directions if practical. When they are not the same, it is sometimes necessary to use diamond shaped gaging pins to allow for greater tolerance in one direction than in the other. By this, it is of course not intended that the engineer should restrict wider permissible tolerances in one direction to the closer tolerances required in another direction, but that uniformly large tolerances should be used in preference to unnecessarily close tolerances when conditions permit.

The quantity of parts to be manufactured will, of course, determine

the extent of the tooling to be provided. Because of prohibitive costs, jigs and fixtures<sup>1</sup> are kept to an absolute minimum for small quantity production.

Reasonably close tolerances on extremely large quantity production may not result in very much increase in cost. The cost of tooling adequate to attain close tolerances, when distributed over a large number of parts, will not affect the cost of individual parts greatly, and may actually reduce the cost of the product by lowering assembly charges. With adequate tooling and proper supervision, reasonably close tolerances can usually be attained with ordinary operators. Close tolerances for a few parts will, on the other hand, require highly skilled mechanics and may require specially made gages. These gages, though kept as low as possible in cost, may appreciably affect the product cost.

**18.4. Gages.** Gages are used to indicate the measure of a dimension of a part or to compare dimensions of two or more parts. Adjustable general purpose gages such as micrometers and vernier calipers, which will measure a range of sizes, are used for job-shop work. Gages of fixed sizes and gages which give very accurate readings by high amplification are used mainly for high production work. Some gages are read directly, others are used for transferring dimensions from one part to another or from a master to another part. The various types will be discussed under the headings: fixed size, nonamplifying, amplifying, circle dividing, and miscellaneous gages.

#### Pin Gage

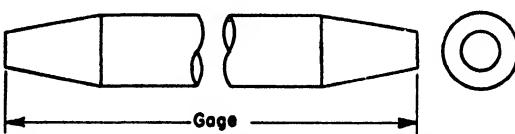


FIG. 18.1. A pin gage for gaging bore diameters.

**18.5. Fixed Size Gages.** These gages indicate the measure of a part by friction contact or lack of contact. The following are examples.

*Pin gages* — end measuring pins for determining bore diameters (see Fig. 18.1).

*Plain plug gages* — for determining hole sizes, normally for holes under 5 in. (see Fig. 18.2). Larger gages are sometimes used for gaging thin parts which may be out of round.

<sup>1</sup> Fixtures are tools for holding or positioning the work for welding, for machining, or for assembly. The word "jig" is sometimes used synonymously with "fixture," but more generally a jig is a fixture for drilling. Besides holding the work, it furnishes a means of quickly and accurately positioning the drills with respect to the work and determines the relationship between holes.

*Plain ring gages* — for determining shaft sizes (see Fig. 18.3).

*Thread gages* — both plug and ring types for determining thread diameter, pitch, etc., on internal and external threads (see Fig. 18.4).

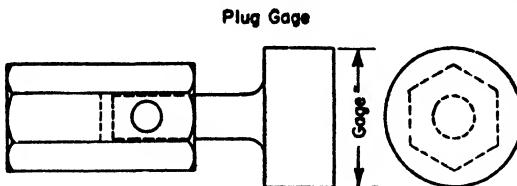


FIG. 18.2. A plain plug gage for gaging holes.

*Snap gages* — for determining diameters and length. These gages usually are designed to measure the two limits for a part. On a snap gage for a shaft, for example, the "GO" size measures the maximum limit for the shaft. This portion of the gage must go over the work without being forced. The "NOT GO" size measures the minimum limit. If the NOT GO portion of the gage passes over the work without force, the work is below the minimum limit (see Fig. 18.5). When gaging a hole, the GO size corresponds to the lower limit, and the NOT GO to the upper limit. The GO size should enter the work, the NOT GO should not.

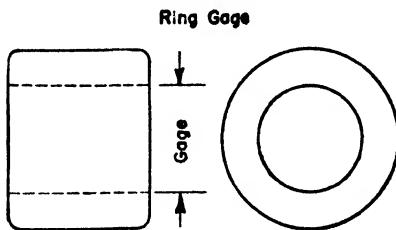


FIG. 18.3. A plain ring gage for gaging shafts.

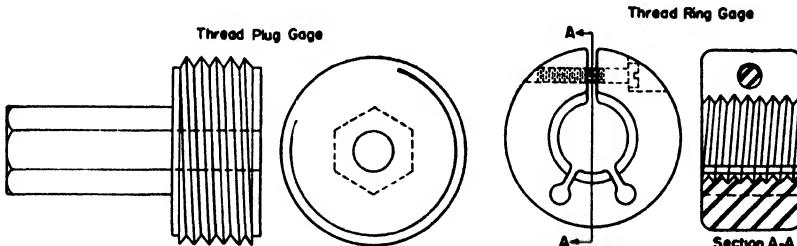


FIG. 18.4. Left is a thread plug gage for internal threads; right is a thread ring gage for external threads.

*Calipers* — for transferring dimensions and comparing dimensions of similar parts. When the caliper has been adjusted to the work size, the distance between the contact points of the caliper is measured to determine the work dimension. Vernier calipers are provided with their own

measuring scale and are designed so that they may be used to measure distances between the caliper surfaces which come in contact with the work dimension.

*Telescoping gages* are similar in purpose to internal calipers. A telescoping plunger is expanded to the size of a hole or slot by a spring in the gage. The plunger is then locked into position for measurement.

*Thickness or feeler gages and gage blocks*. Feeler gages consist of a number of thin metal blades each of a different thickness, and in the desired number of dimensional steps. They are used for checking clearances. Gage blocks are used mostly for reference in setting

gages and for accurate measurements in tool, gage, and die manufacture. Each block is made from hardened steel, and the parallel sides are accurately lapped within a few millionths of an inch of the nominal size. (Laboratory sets are within two millionths.) They are assembled in various combinations.

*Tolerances on fixed size gages*. It is not commercially practicable to make a fixed size gage to an absolutely exact dimension. Consequently, a tolerance must be permitted on the gage size. This tolerance will affect the accuracy of gaging the workpiece and so should be specified in accordance with the required accuracy of the work. The wear of the gage has a similar influence and must also be provided for in establishing gage tolerances.

For precision work, it is common practice to limit the gage tolerance to 10 per cent of the work tolerance, when gage tolerances are not specified by the purchaser, and when the tolerance so determined does not exceed the maximum standard for accepted gage manufacture. The tolerances for plain cylindrical plug and ring gages have been standardized by the ASA into five classes according to accuracy. The tolerances for these classes are given in Table 18.1 for several ranges of nominal sizes.

Gages of class XX are precision lapped and are used for final inspection and reference. For gages from class X to class ZZ, the tolerances become increasingly greater, and the gages are used for inspecting parts having increasingly larger tolerance limits. The cost of gages is directly proportional to the accuracy to which they are made, so class Z gages are less expensive than class X. The gage specification should therefore never call for a gage having a closer tolerance than the inspection operation justifies.

Snap Gage

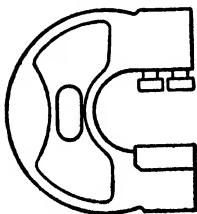


FIG. 18.5. A snap gage.

The first anvils check the "GO" limit, and the second anvils check the "NOT-GO" limit.

The bilateral and unilateral methods of specifying tolerances have both been used for gages. The former is now practically obsolete, and some form of the latter is used by most gage manufacturers. Some of the methods in common use are illustrated in Fig. 18.6. The unmodified unilateral method, although requiring the product manufacturer to work to closer limits, is the only system by which the work tolerance can be strictly maintained.

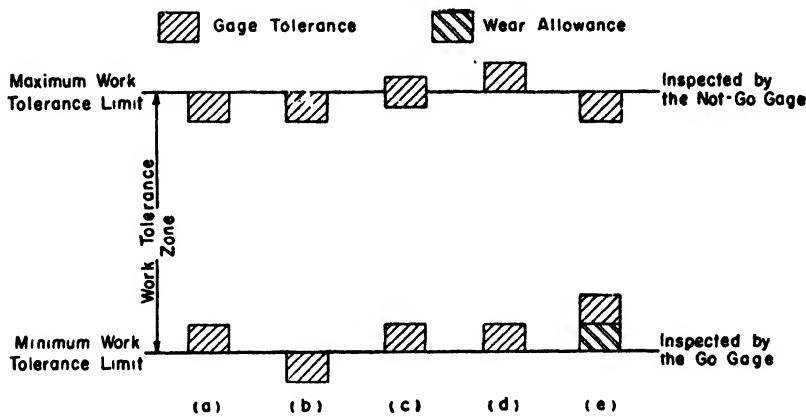


FIG. 18.6. Methods of specifying gage tolerances for plug gages. (*Compiled by The Sheffield Corporation.*)

- Unmodified unilateral system.
- Commercial plain ring gages (the maximum limit for a ring gage would be checked by the "GO" gage rather than the "NOT-GO").
- Commercial plain plug gages.
- For thread gages.
- Unilateral system showing gage tolerance and wear allowance.

TABLE 18.1

Nominal size, in.		Gage Maker's Tolerances				
Above	To and including	Class XX (male gages only)	Class X	Class Y	Class Z	Class ZZ (ring gages only)
0.029	0.825	0.00002	0.00004	0.00007	0.00010	0.00020
0.825	1.510	0.00003	0.00006	0.00009	0.00012	0.00024
1.510	2.510	0.00004	0.00008	0.00012	0.00016	0.00032
2.510	4.510	0.00005	0.00010	0.00015	0.00020	0.00040
4.510	6.510	0.000065	0.00013	0.00019	0.00025	0.00050
6.510	9.510	0.00008	0.00016	0.00024	0.00032	0.00064
9.510	12.510	0.00010	0.00020	0.00030	0.00040	0.00080

Wear allowances, when considered, are added to the tolerances in such a way as to compensate for the loss of gage material due to wear. The wear allowance should thus be added to the nominal diameter of a plug gage and subtracted from that of a ring gage. It is customary to make an allowance for wear only on GO gages, since NOT GO gages will sustain practically no wear. It is also common practice to allow more wear allowance for working gages than for inspection gages because the grit and other abrasive materials present and the extra gaging operations required cause gages to wear faster in the shop. The safe method of allocating the wear allowance is to apply it before the tolerance, and to apply it unilaterally so that the gage zone will remain within the work tolerance (see Fig. 18.6e).

**18.6. Nonamplifying Gages.** Metal rules, depth gage rules, vernier scales, and vernier height gages may all be considered nonamplifying gages. They are graduated metal rules with suitable means for measuring dimensions optically; they have many general purpose applications to laying out and measuring work, especially that not requiring tolerances.

**18.7. Amplifying Gages.** For convenience, the various types of these gages are classed as: fixed pressure contact type, resistance to air flow type, and optical type.

*Fixed Pressure Contact Type.* Comparators are the most widely used gages in this class. They are designed so that they can be adjusted to the nominal dimensions, possibly with the use of gage blocks, and their amplifying mechanism indicates the variation of the measured pieces from this dimension. The indication given may be that the part measured is within the tolerance zone, or, if not, that it is undersize or oversize. This type is known as a limit comparator. More commonly the measurement is evaluated on a dial or scale, as on the indicating comparator. Gages of this type are largely used for quantity production.

There are many designs on the market. The amplification of the difference between the gage setting and the work may be obtained by mechanical or optical levers, by a rack and gears, by stretching and unwinding a twisted ribbon containing the indicating needle, by an electromagnetic pickup (Electrolimit), by the shadow of a special reed lever, and by a fluid column. In addition, the comparator may be made in the form of a snap gage, a plug or ring gage, or it may be built into a suitable stand for external or internal dimensional comparisons.

Another type of amplifying gage that depends on fixed pressure contact is the micrometer. It is a common general purpose gage and

may be made in various forms for internal, external, and screw thread measurements, and depth reading.

*Resistance to Air Flow Type.* These gages may be used to check taper, bell-mouthing, and out-of-roundness, as well as the average diameter of internal holes. A gaging plug slightly smaller than the minimum limit is put in the hole and a filtered and pressure regulated supply of air is admitted to the plug from which it escapes through two nozzles which are located diametrically opposite each other in the plug. The clearance between the gaging member and the hole determines the amount of air discharged. As the volume of escaping air is decreased, the back pressure is increased and the amount of pressure drop over the nozzles is therefore lessened. This drop in pressure is registered on a precision pressure indicator which can be calibrated in terms of the clearance, thus forming a measure of the hole size. For limit comparisons, the dial need be calibrated only for the two limits. Present means for indicating the pressure drop or the volume of air flow in these gages include (a) a Bourdon tube pressure gauge, (b) a transparent vertical tube of increasing cross-section in which a float takes a position according to the air flowing past it, and (c) a water column, the height of which indicates the flow of air past a venturi meter in the gauge line.

*Optical Type.* The toolmaker's microscope and the universal measuring microscope are examples of optical amplifying gages. Both use a microscope with "cross hair" lines as a means for locating the work surface which is to be measured. The toolmaker's microscope uses micrometers and gage blocks to measure coordinate distances on the work. The universal measuring microscope uses graduated glass scales, and spiral lines on graduated dials in microscopes to measure coordinate distances. Both are equipped with protractors for angular measure.

Another type of optical amplifying gage is the projection measuring machine. It uses a magnified shadow of the work, and micrometers and gage blocks for coordinate measurements. With a chart on the projection screen, deviation of the work from a prescribed contour can be determined. Some projection measuring machines have the following equipment or attachments: protractor screens for angular measure, opaque illumination for measurements on the surface of the work (not the outside contour of the work), photograph attachment for photographing work images, and tilting means for helical work.

**18.8. Circle Dividing Gages.** The following means are available for obtaining and measuring divisions of the circle.

*Machinist's bevel protractor.* This gage is graduated in degrees.

*Toolmaker's universal bevel protractor.* This type of gage contains a vernier graduated to 5 min.

*Optical bevel protractor.* The scale is magnified optically.

*Geared dividing head.* This is used for milling machines, etc. (See Chapter XVII.)

*Optical dividing head.* Dividing heads of this type are used primarily for inspection.

*Protractor attachments* for measuring microscopes and projection measuring machines (see Sec. 18.7).

**18.9. Other Measuring Devices.** Only three types of measuring devices other than those already discussed will be mentioned here. They are optical flats, templates, and gear measuring machines. A tool and gage shop might have these and other special measuring devices, depending upon the work they normally do. Weighing scales and accurate balances, for example, are required in some shops.

*Optical Flats.* An optical flat is a precision polished flat disk, usually of natural quartz, that is used primarily for testing the flatness of plane, accurately lapped surfaces. When the optical flat is placed on the surface, the incident light is reflected both from the bottom of the flat and from the surface of the work visible through the flat. Interference between the two reflected rays causes characteristic bands, called Newton's rings, to appear. If the light used is monochromatic (single color, narrow wavelength band), the interference bands will be dark in color. When the surface being tested is irregular, the distortion of the bands will indicate the location and extent of the irregularities.

*Templates.* Templates are thin metal gages into which the cross-sectional profile of some finished contour is cut. The accuracy of the contour may be checked at various points either by noting the correspondence with the template, by observing the light that will pass between the contour and the template, or by probing with feeler gages.

*Gear Measuring Machines.* Machines used for measuring and checking gears include the following:

**THE INVOLUTE CHECKER.** This machine measures the deviation of gear tooth profiles, or cams, from a true involute.

**THE LEAD CHECKER.** The lead checker is used to measure the lead and pitch of screws, hobs, worms, etc.

**THE RED LINER.** This machine is used for charting the changes in center distances of tightly meshed gears as they are rotated. The changes in center distance may be caused by inaccuracies of pitch, tooth contour, eccentricity between hub or shaft and pitch circle, etc.

**HAND ROLLING FIXTURES.** These are for determining the accuracy of bevel and hypoid gears.

**18.10. Material for Gages.** Gages are usually made from tool steel, machine steel, or high speed steel. Each of these grades makes possible the hardening of the gaging surfaces, and thus reduces wear and results in long gage life.

Since most of the work made in the shop is iron or steel, the use of steel gages has the advantage that the coefficient of expansion is approximately the same as that of most of the work. This is important because changes in temperature will cause the size of both the work and the gage to vary. The gages having been set at a standard temperature of 68 F will seldom be used at that temperature in the shop. But if the gage is correct at the reference temperature and the coefficient of expansion of both the work part and the gage is approximately the same, there is no danger of error as long as both the work and the gages are at the same temperature when the measuring is done. Gages which are handled often may be protected from the heat of the hand by insulating handles.

**18.11. Inspection.** The function of accepting or rejecting work on the basis of how well it measures up to established specifications or standards is known as inspection. Inspection is a necessity in manufacturing because it assures the maintenance of product quality at the desired level and prevents the use of parts containing defective workmanship or defective material.

There are four main points in the manufacturing cycle at which inspection may be incorporated. In repetitive manufacturing, the first few parts produced when each operation is started may be inspected for defective workmanship so that only the minimum number of parts will be spoiled in setting up the job. The output of the repetitive machine is then intermittently inspected to assure continued production of acceptable work, and to prevent spoilage.

The second point at which inspection may be used is in checking batches or units of semifinished parts so any defective material may be set aside and no additional work done on it until a decision has been made as to whether it can be repaired or must be scrapped. In this way the cost of subsequent operations is not wasted on a part which is already defective.

The third point of inspection is at the assembly operation. This inspection prevents assembly of defective parts which would slow up assembly work, or require dismantling or repair of the product.

The fourth inspection is the final inspection of the finished product after it has been assembled. This inspection assures that no parts have been damaged during assembly and that the product functions properly. For some products it may be necessary first to operate the finished assembly and then to dismantle it for this inspection.

Inspection, like insurance, is an expense which must be justified by the need for it. Simple products require little inspection. Intricate mechanisms in which there are many chances for error require much inspection.

The percentage of parts inspected, that is, the possibility of inspecting samples, depends on the likelihood of error in the parts. Tool wear, the number of tools operating on the part at the same time, how frequently the machine needs readjustment, how much the operator's attention and skill affect the accuracy of the product, the amount of experience of the operator — all these affect the percentage of sampling inspection of machine parts. Bulk or batch parts are almost always inspected by sampling.

Inspection of dimensions is, of course, accomplished with gages. Since the gages used during manufacture must never pass work which would be rejected by the inspection gages, the manufacturing gages must be at least equally critical or more critical of the work — that is, slightly inside the product limits.

The soundness of materials may be inspected nondestructively by magnetic and fluorescent tests for surface or near surface cracks, and by the X-ray and gamma ray examination for internal defects such as blow holes, sand holes, and pipes. These tests are briefly described in Chapter XII.

**18.12. Conclusion.** The responsibility for establishing correct dimensions, tolerances, and fits rests with the engineer. In all mechanical design there is no more important step than the selection of these relationships. They affect the facility with which the shop can produce acceptable parts, they influence the kind and degree of gaging, and they are paramount to proper functioning and long life of the product. They also directly influence the cost of manufacture and of handling complaints and in that way partly determine the cost of the product. When the engineer is not sure of the method of dimensioning best suited to the process, when he does not know the inherent accuracy of the processes to be used, or when he is not familiar with the most convenient method of gaging, he should by all means take time to find out these things before completing his specifications.

#### REFERENCES

- "Tolerances, Allowances, and Gages for Metal Fits," B4a, American Standards Association, 1925.
- "Gages," Pratt & Whitney.
- "Sheffield Gages," The Sheffield Gage Corporation.

**CONTROL OF QUALITY BY STATISTICAL METHODS**

By R. E. WAREHAM

**18.13. Introduction.** The control of quality of manufactured products is an old problem. It was present in the days when articles were produced by hand, and it has been accentuated by machine production because of the rapidity of manufacture and the variables in machine methods.

Adequate gaging and inspection are recognized as being essential to maintaining good quality. Unless some quantitative measure of the product can be secured, it is impossible to judge quality fairly and consistently at a given time or to compare that quality with past or future performance.

Over a period of many years, industry has developed to a high degree methods for gaging, inspection, and test of manufactured products. Recently, a method of analysis based on the principles of probability and statistics has been used to analyze inspection results for the purpose of obtaining better control over product quality. Development and use of this method, called the *statistical method for quality control*, started in 1924 in the Bell Telephone Laboratories. A number of applications in different industries by various companies have demonstrated its applicability to a wide variety of industrial quality control problems and have given definite evidence of its practical value. Some of its applications are briefly described in this chapter.

**18.14. Applications.** The primary purpose of inspecting a product is, of course, to determine its acceptability, i.e., how closely it meets engineering specifications. Analysis of the results from inspection tests by the statistical method may be used as the basis for purposeful control of quality during subsequent manufacture in two general ways:

(1) If some units of product fail to meet engineering specifications (and are therefore called defective), a careful study of inspection records will often indicate trouble in the manufacturing process which may be corrected before production is completed, thus reducing the per cent of defective parts over a period of time.

(2) If, on the other hand, inspection tests show all units conforming to specifications, an analysis of the way units vary within the tolerance range may be of value in specifying the permissible tolerances, or the amount of inspection required.

The constant plague of a mass production process is trouble that enters the process unannounced and leaves the same way. While in the process, such trouble causes considerable waste and interferes with production schedules. Once trouble has entered the process, there is gen-

erally difficulty in finding out just what is wrong and sometimes it is impossible to identify the trouble at all. However, careful and continuous study of inspection data by means of quality control methods may be of help in avoiding such troubles, thereby extending the benefits of mass production.

Interchangeable parts manufactured in large quantities and in a continuous stream often involve the use of automatic machinery, where it is essential (a) that the setup of the machine be correct at the time of starting production, and (b) that the machine continue producing units of the proper dimension during its entire run. Periodic tests on output of the machine during the run are necessary to indicate that the quality level is being maintained.

The function of statistical methods in controlling quality of such manufactured parts is to insure that these conditions are met. Use of these methods enables the quality of machine output to be determined early in the stage of its operation and gives a criterion for shutting the machine down before large amounts of defective material are manufactured.

For many quality measures such as dimensional measurements of metal parts and resistance tests of relays, 100 per cent inspection is possible and desirable. There are other situations where only sampling can be carried out because the test is destructive (e.g., tests to determine the life of electric lamps or the tensile strength of steel). There are still others where complete conformance to a specification by each individual piece is not absolutely necessary (e.g., painted surfaces of incoming materials).

The amount of inspection basically required for a given product depends on (a) what quality level must be guaranteed to the consumer of the product, (b) what quality is inherent in the process, and (c) the economic usefulness of the product. In those instances where sampling is done, the sample must be carefully analyzed to give an accurate indication of the quality of product that was *not* inspected. Accurate prediction of product quality on the basis of sampling tests can be made if test results for successive samples show that quality is "controlled."

**18.15. Controlled Quality.** By definition, *quality is controlled when, on the basis of past experience, it is possible to predict how the product will vary in the future.* When this state of control is realized, the process is operating at high manufacturing efficiency and engineering effectiveness. The advantages secured are reduction in the cost of rejections, reduction in the cost of inspection, attainment of the maximum benefits from quantity production, attainment of uniform quality under all conditions, and reduction in tolerance limits.

Though quality control methods are based on the laws of probability and statistics, practical application has been greatly simplified through several recent publications.<sup>1</sup> With these, only a limited knowledge of the basic probability concepts is necessary to understand the type of variations found in an industrial production process operating under control. Such an understanding may be drawn from the well-known coin problem, involving the chance of throwing heads. The chance of throwing heads in a single toss is one half. It has a counterpart in the chance of making a defective unit of product in a given production process. If a sample of say 20 coins is thrown at once, the percentage of heads in the sample will not always be the same. Likewise, the percentage of units defective in the production process may vary from time to time, owing solely to chance causes. Variations of the type found in pure chance situations (such as the coin problem) are designated as due to "chance causes," and a manufacturing process having variations within chance limits is said to be under control. Variation outside of chance limits is said to be due to "assignable causes."

The problem of quality control is to indicate whether assignable causes are present in a given manufacturing setup. Then, by engineering investigation, these assignable causes can usually be eliminated from the production operation. Once this is done, the quality of units turned out will be uniform and future quality can be accurately predicted.

It is emphasized that the statistical methods used in quality control are not a substitute for good judgment or processing skill, but rather are tools to secure effective use of these.

**18.16. Specific Problem.** As an example of the way in which these methods may be applied, consider the problem of producing a small screw machine part on an automatic screw machine. The permitted tolerances on the length of the part are  $1.425 \text{ in.} \pm 0.005 \text{ in.}$  A sample of four pieces is taken hourly at the machine, and the length of each piece is measured. Table 18.2 gives the measurements for 27 samples of four tests each, showing also the average length and range (difference between largest and smallest measurements) for each sample of four.

It will be noted from this table that there are variations from one sample of four tests to another sample. This is clearly shown by the averages for the various samples, e.g., the average measurement for Sample 1 was 1.42425 in., whereas for Sample 2 the average was 1.425 in., and for Sample 3, 1.42575 in. The changes in hourly averages have time (and factors associated with it, such as tool wear) as the only cause for variations in excess of chance limits.

Similarly, there are variations among the four tests in an individual

<sup>1</sup> See references at end of this section.

sample. This is indicated by the range of measurements within successive samples, Sample 1 having a range of measurements equal to 0.003 in., Sample 2 having a 0.004 in. range, and so on.

The purpose of quality control analysis of these measured length tests is to show whether variations from one sample of four tests to the

TABLE 18.2. LENGTH MEASUREMENTS ON A SMALL SCREW MACHINE PART

Samples Tested (taken hourly)	Test Number (Thousandths of an inch in excess of 1.400)					Range (thousandths of an inch)
	1	2	3	4	Average	
1	24	26	24	23	24.25	3
2	25	23	27	25	25.00	4
3	28	24	25	26	25.75	4
4	22	26	24	25	24.25	4
5	20	23	24	24	22.75	4
6	25	24	23	24	24.00	2
7	23	25	23	22	23.25	3
8	24	22	21	25	23.00	4
9	22	21	22	22	21.75	1
10	21	22	24	25	23.00	4
11	23	21	25	24	23.25	4
12	23	24	23	26	24.00	3
13	24	26	22	25	24.25	4
14	22	24	25	24	23.75	3
15	24	29	22	25	25.00	7
16	23	27	24	27	25.25	4
17	23	24	25	26	24.50	3
18	23	25	23	23	23.50	2
19	25	24	25	24	24.50	1
20	25	24	25	24	24.50	1
21	25	24	23	23	23.75	2
22	23	24	26	24	24.25	3
23	27	26	24	25	25.50	3
24	25	24	21	24	23.50	4
25	26	24	25	22	24.25	4
26	23	25	18	24	22.50	7
27	23	24	26	23	24.00	3
Total					647.25	91
Average					23.97	3.37

next such sample may be expected to be due to chance causes or whether they must be due to an assignable cause. The analysis is carried out by comparing such variations from one sample to the next with variations within a single sample of four tests, thus constituting a test to show whether hourly measurements show any trends over a period of time.

The averages for hourly tests should be plotted on a "control chart" in chronological order as shown by Fig. 18.7. Note that the samples are in order along the  $x$ -axis and the averages plotted as corresponding ordinates. Then, to evaluate whether measurements over the 27-hr period show the presence of an assignable cause, "control limits" are plotted on the chart. These are set on the basis of the control chart practice recommended in American War Standard Z1.3 prepared by the American Standards Association, New York.

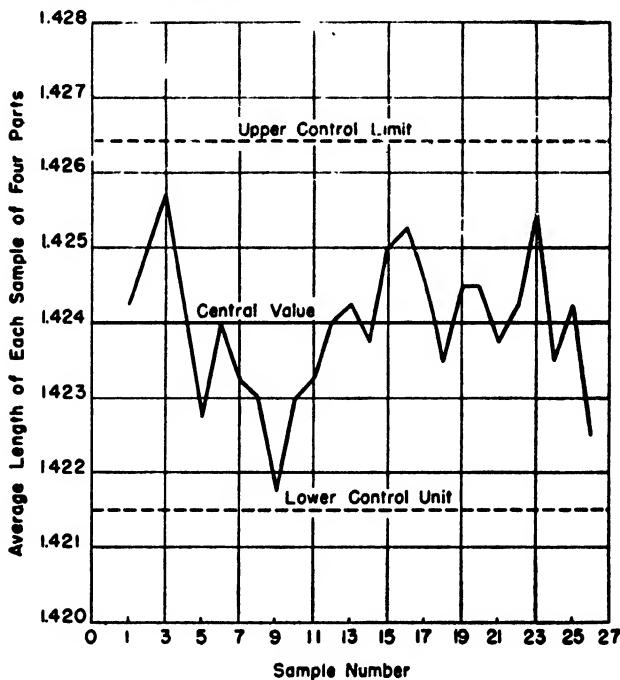


FIG. 18.7. A control chart for length tests on a screw machine part.

These control limits are symmetrical about the average dimension for all samples (1.42397 in.) rather than the nominal dimension of 1.425 in. The average dimension is used as a central value, because it is desired to know whether samples tested show control with respect to one another, i.e., are from a uniform batch of parts. If samples do show such control, a change in machine setup would be required only if it were found necessary to increase the average dimension from 1.42397 in. to 1.425 in.

The upper control limit was determined to be 1.4264 in. for this problem and the lower limit was 1.4215 in. It will be noted from the

control chart that all sample averages fall within control limits and hence the process may be said to show statistical control.

**18.17. Frequency Distribution.** In quality studies it is often advantageous to prepare a "frequency distribution" of the measured characteristic (in the example above, length of the part). Such a frequency distribution consists of a tabulation of the number of times each measurement occurs in the total number of tests. It may conveniently be prepared in tabular form by placing a mark opposite each dimension for each test — grouping the marks by five's. When the count of frequencies for each dimension is complete, a graphical indication (Table 18.3) is available of the spread of the tests through the tolerance range.

TABLE 18.3. FREQUENCY DISTRIBUTION  
LENGTH MEASUREMENTS ON A SMALL SCREW MACHINE PART

<i>Length Dimension (inches)</i>		<i>Frequency</i>
1.415		
16		
17		
18	1	1
19		
20	1	1
21		5
22	-       1	11
23	-       -       -	20
24	-       -       -       -       1111 1	31
25	-       -       -       - 111	23
26	-	10
27	1111	4
28	1	1
29	1	1
30		
31		
32		
33		
34		
35		
Total		108

In the frequency distribution for this part, it will be noted that more tests showed a measured length of 1.424 in. than any other single length. (This also happened to be very nearly the average for all tests.) Similarly, only a few tests were very far from this central length, e.g., one at 1.418 in., one at 1.420, five at 1.421, etc. The specified tolerance was 1.425 in.  $\pm$  0.005 in. or from 1.420 in. to 1.430 in., so all except one test (1.418) fell within the tolerance range and would have been

accepted. Thus the number defective was one in 108, or less than 1 per cent.

A graphical method of showing a frequency distribution as a "frequency curve" sometimes illustrates the variation of measurements within a given tolerance range more clearly than do the numbers indicating the frequencies. Such a frequency curve for these 108 length measurements is shown on Fig. 18.8.

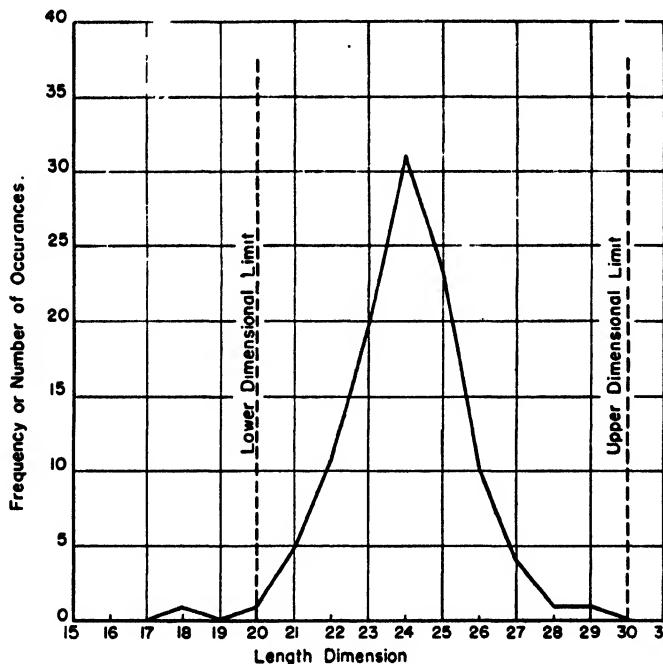


FIG. 18.8. Frequency curve showing frequency of occurrence of each length measurement of a screw machine part.

Variations in quality are present in all manufacturing owing to chance causes. The engineer should use a knowledge of these variations in setting his manufacturing limits, so that only a small amount of product will be rejected at inspection while at the same time assembly and field complaints are kept at a minimum.

**18.18. Conclusion.** Only a brief discussion of the principles of statistical quality control has been possible here. For practical application of the techniques, reference to a few important books and publications on the subject will supply essential information for making direct applications.

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## REVIEW QUESTIONS

1. Explain how interchangeability facilitates low unit cost manufacture in mass production.
2. Define a tolerance, a limit, and an allowance. What are shop-run tolerances? In a fit where tolerances are specified on the fit dimension of each mating part, what fit relation is considered the allowance?
3. How do unilateral and bilateral tolerances differ? Which is most common in industry?
4. What are gages? Describe a pin gage. A plug gage. A ring gage. Explain GO and NOT-GO gages.
5. In general, what relation should exist between gage tolerances and work tolerances? What system is usually used for specifying gage tolerances? How should wear allowances be specified?
6. Describe several types of amplifying gages, including fixed pressure contact comparators, resistance to air flow gages, and optical gages.
7. What type of gaging is done with an optical flat?
8. From what material are gages usually made? How is the problem of work expansion due to temperature changes handled in gaging practice?
9. What is inspection? Discuss the points during the manufacturing cycle at which inspection might be incorporated, and indicate the advantages that can be obtained.
10. What is the function of the statistical method of quality control? In what two general ways may this method be used for the purposeful control of product quality?
11. What is meant when it is said that a process is operating under control?
12. What are chance causes? Assignable causes? Which are detected by statistical methods?

## CHAPTER XIX

### CLEANING, PLATING, AND FINISHING OF METALS<sup>1</sup>

#### CLEANING OF METALS

The methods of cleaning discussed include methods for removing oil, grease, and buffing compounds, sand and grit blasting, and pickling.

**19.1. Methods for Removing Oil, Grease, and Buffing Compounds.** Three general methods for cleaning metals contaminated with oil, grease, or buffing compounds are (*a*) vapor degreasing, (*b*) emulsifiable solvent cleaning, and (*c*) aqueous alkaline cleaning. They may be used individually or in combination, depending upon the material to be cleaned and the effects desired. Cleaning previous to plating, for example, should be complete, and the work should show no "water-break" (on removal from water, the work should be covered by a continuous water film), whereas the requirements for cleaning previous to japanning or enameling are not so rigid. Each type is in commercial use, with alkaline cleaning being used most generally.

*Vapor Degreasing.* In the vapor degreaser, a noninflammable solvent, such as trichlorethylene, is heated to boiling, electrically, or by steam coils, in a chamber around the top of which is provided cooling coils or compartments to recondense the hot vapors and prevent escape of the solvent. The work to be cleaned is hung in the hot vapor which condenses upon the work and washes off the grease and oil. Because the oils removed are only very slightly volatile at the operating temperature of the degreaser, the hot vapor will be essentially that of clean solvent, although the liquid solvent itself may be very badly contaminated. The volume of solvent condensing upon the work to be cleaned, and consequently the effectiveness of cleaning, is determined by the weight of the metal, its specific heat, the temperature rise necessary to bring the work to the temperature of the solvent, and the latent heat of condensation of the solvent. For a given metal and cleaner, the amount of vapor condensed will be dependent upon the weight of the metal to be cleaned. Thin sheets of metal containing heavy films of oil will therefore be cleaned either poorly or not at all, whereas heavy gage sheets and plates with comparatively heavy grease films may be effectively cleaned. The vapor cleaner has a second disadvantage in that it does

<sup>1</sup> Compiled by C. Dantsizen.

not completely remove solid dirt from the surface, and frequently the work may be well cleaned of oil, but a cloud of solid dirt may adhere to the work, necessitating a subsequent wiping operation.

To overcome the difficulties mentioned, combinations of two solvents, or a sequence of boiling liquid, cold liquid, and hot vapor may be employed. The work is first immersed in the boiling solvent, where most of the solid dirt and oil are removed. This cleaner soon becomes contaminated but the cleaning efficiency of the system is not seriously affected. The work is transferred from the chamber containing the hot solvent to a chamber containing relatively clean cold solvent, which is formed by the condensation of the vapor from the first cleaner. In this chamber, the work is cleaned of dirt which was not removed in the first chamber. The work withdrawn from the cold chamber is held above the hot compartment, where the hot, clean vapor condenses and removes any residues of oil not removed in the cold chamber. This sequence, although requiring more labor for cleaning than the simple vapor cleaning, has proved itself in practice, and allows thin, badly contaminated work to be successfully cleaned.

Vapor degreasing has several advantages: (1) The drying of the work after cleaning is rapid, which is of particular value for recessed work or where water stains might be objectionable; (2) the high temperature of operation softens the solid fats and lowers the viscosities of the oils, allowing rapid penetration and removal of material in holes or crevices, removal of which would be difficult with alkaline aqueous cleaners; (3) metals such as aluminum or zinc which are attacked by the alkaline cleaners may be cleaned by vapor degreasing with almost no visible effect upon the finish; and (4) the installations may be made automatic and are cleaner than alkaline cleaning setups. Vapor degreasing has found particular value for cleaning of metal previous to lacquering, japanning, enameling, and general organic finishing, but must be followed in cleaning previous to plating by an alkaline cleaner to remove traces of organic matter which remain on the surface after degreasing. Other disadvantages of vapor degreasing are: (1) Increased cost of materials over alkaline cleaning; (2) difficulty in removing solid dirt; (3) necessity for distilling apparatus for keeping the solvent clean, especially where large volumes of dirty work are cleaned; and (4) toxicity of the solvent (this may be troublesome in poorly designed equipment).

*Emulsifiable Solvent Cleaning.* The removal of smut from cold rolled steel and the general removal of solid particles and oil from both ferrous and nonferrous metals have been difficult problems. The use of emulsifiable solvent cleaners has proved effective in problems of this type.

Emulsifiable solvent cleaners are miscible with oils and can be washed off with water, although a slight film of oil may remain upon the work and necessitate a subsequent alkaline cleaning treatment before electroplating. The cleaners may be of two general classes. One class is composed of a hydrocarbon-soluble emulsifying agent, such as sulphonated corn or castor oil, acid sludges, or triethanolamine oleate, added to an organic solvent such as high-flash naphtha or kerosene. The second class is made by "blending" a soap, such as potassium oleate, with an organic solvent, such as kerosene, using such blending or coupling agents as cresylic acid, butyl alcohol, cyclohexanol derivatives, or butyl cellosolve. As much as 10 per cent water may be added to increase the ease of emulsifying.

The work to be cleaned is immersed in the solvent cleaner, where some of the oil is dissolved and each solid particle thoroughly wetted; then it is removed, allowed to drain, and then rinsed in clean running water. A second rinse in clean warm water may follow, after which the work is usually suitable for enameling, japanning, etc. For electroplating, the work is transferred from the running rinse directly into an alkaline cleaner to remove any traces of remaining organic matter. The solvent cleaner can stand considerable contamination from oil and may be used for months.

Emulsifiable solvent cleaners are particularly valuable for cleaning chemically active metals, such as lead, aluminum, and zinc, since the cleaners are only slightly alkaline and do not attack these metals. The cleaners are nonexplosive and are much safer from the standpoint of fire hazard than naphthas, benzene, etc., and they do not have the toxic effects of carbon tetrachloride. Solvent cleaners will not clean satisfactorily if the work is wet, and the cost of "drag-out" may prohibit their use for work containing wells or pockets.

*Alkaline Cleaning.* An exact understanding of alkaline cleansing processes has, as yet, not been realized, but certain factors have been recognized which indicate in various degrees the relative cleansing values. These factors are:

PENETRATION OF THE DIRT LAYER. The rate of penetration is greatly influenced by the temperature of the solution and the interfacial surface tension.

WETTING OF THE SURFACE. Good wetting power of an alkaline cleaner is usually accompanied by low interfacial surface tension of the solution.

EMULSIFICATION AND DEFLOCCULATION. Without emulsification of the oils and greases, deflocculation, and suspension of the solid dirt in the solution, the penetration and wetting power would be of little value.

**FREE RINSING ABILITY.** The poor rinsing qualities of certain soaps, such as the stearate soaps, limit their use in commercial cleaning.

**SAPONIFICATION.** The value of saponification in alkaline cleaning has been overestimated. Vegetable or animal fats or fatty acids may be removed to some extent by saponification, but the bulk of metals to be cleaned is contaminated with unsaponifiable mineral oils or insoluble soaps and dirt which cannot be saponified and are removed by the mechanisms of wetting, emulsification, and deflocculation.

The essential components of a good alkaline metal cleaner are (1) a source of available alkali, (2) a buffer to control the alkalinity, and (3) a soap. The source of alkali is most economically furnished by caustic soda. For mild cleaners, sodium metasilicate or sodium sesquisilicate may be used to advantage. Sodium carbonate or sodium sesquicarbonate and trisodium phosphate are not economical sources of alkalinity calculated on an equivalent sodium oxide basis.

A constant *pH* or alkalinity is desired throughout the life of the cleaner, and this may be controlled to some measure by the use of substances with buffered alkalinity such as sodium tetraborate, disodium phosphate, or sodium meta-, sesqui-, or orthosilicate, depending upon the *pH* level desired.

Soaps such as sodium resinate, sodium linolenate, or sodium oleate, and soaps from coconut, palm, whale, and fish oils increase the wetting power and are the most valuable aids for emulsification. The choice of soap depends upon the condition of service. The properties to be considered are: solubility, optimum cleaning temperature, lather formation, stability, rinsing qualities, hydrolysis, detergent ability, and cost. Rosin has been used extensively, for example, because of its low cost, good solubility, nonfoaming tendencies, and ease of rinsing. Sodium stearate, on the other hand, has found little application in alkaline metal cleaners because of its strong lather, low solubility, and poor rinsing qualities. Numerous new synthetic wetting agents have appeared within the last few years, but many of these lack the ability to deflocculate and suspend dirt although possessing excellent wetting properties. The high cost of these synthetic agents has limited their application in metal cleaning, although they are being used in textile cleaning. Some of these materials are sulphates of higher fatty acids, or naphthalene sulphonate derivatives.

Laboratory test methods for determining the relative cleaning ability of various alkaline cleaners have included measurements of surface tension, measurement of the colloidal properties, washing of soiled cloths, measuring the rate of settling of carbon, and the deflocculating

action against graphite. These methods are not of sufficient value to determine the relative detergent actions for commercial metal cleaning problems. When performing factory trials on cleaners, the temperature of operation, as well as concentrations, must be carefully watched. Too high concentrations may actually clean more poorly than lower concentrations, and it may be noted that cleaning ability does not necessarily increase with increased alkalinity. Cleaners with mild alkalies may clean more efficiently than high caustic cleaners. The cleaning trials should be continued for some time, since some cleaners maintain an almost constant detergent efficiency, whereas others rapidly decrease in cleaning ability because of poor buffering or too stable emulsification of the oil, from improper choice of the soap used. The foaming and rinsing qualities should be noted as well as the cleaning ability.

For cleaning zinc, aluminum, lead, or tin, the milder alkalies such as metasilicate or trisodium phosphate are used, often together with free rinsing soaps. The  $\text{pH}$  range may be from 8 to 10.5. Light duty and electroplaters' cleaners range in  $\text{pH}$  from 10.5 to 12.5 and heavy duty cleaners range in  $\text{pH}$  from 12 to 13.5. Whale or fish oil soap solutions are frequently used as soak solutions either with or without agitation to remove buffing compounds or heavy dirt previous to the use of alkaline cleaners.

The cleaning action of alkaline cleaners may be greatly speeded up by using the alkaline solution as the electrolyte for an electrolytic cell in which the part to be cleaned is one electrode. Parts from soft metals, such as lead, zinc, and tin, must necessarily be cleaned cathodically (object negative electrode) because they would be badly etched if cleaned anodically (object positive electrode). Steel may be cleaned either anodically or cathodically. At the cathode a greater amount of gas is liberated than at the anode, and the hydrogen has some reducing action on oxides present. Some difficulties that may be encountered are hydrogen embrittlement and plating of a smut upon the work due to the deposition of iron, copper, and other metals that may accumulate in the cleaner after it is used. Reversal of the current will not completely remove these smuts but will oxidize metals in the smut so that they will be more readily removed in the acid dip that follows. Anodic cleaning is receiving favor because of absence of embrittlement and smut deposition.

In electrocleaners, the tank should not be used as an electrode, but separate anodes of iron or nickel should be used to prevent attack upon the tank. Chlorides should be carefully avoided and the soap content should be low or else excessive foaming, with danger of an explosion,

may result. The current densities employed range from ten to one hundred amperes per square foot with the higher current densities giving more rapid cleaning action.

**19.2. Sand and Grit Blasting.**<sup>1</sup> Blast cleaning involves the forcing of a stream or spray of sand or other abrasive material against the surface of metal, stone, and other materials by means of compressed air. In general, metal surfaces that are to be painted, lacquered, plated, galvanized, or vitreous enameled require a blast cleaning treatment to obtain a really good bond between the surface and the finish applied.

*Abrasive Materials.* For sand blasting, only the very best grades of silica sand should be used as there is no economy in using inferior grades; they have neither the cutting qualities required nor the mechanical strength to withstand successive impacts. Steel abrasives are divided into two classes, namely, steel grit which is angular, and steel shot which is spherical, and from which, through a crushing action, steel grit is produced. Opinions differ as to the relative merits of sand and grit. Undoubtedly under certain conditions each type of abrasive may have advantages over the others, and so general results without full details may be misleading. It is known that one ton of steel abrasive will do the work of one carload of the best sand-blast sand. Other advantages for steel abrasives are increased production, reduced air cost, reduced abrasive cost, reduced nozzle cost, and the elimination of silicosis (a disease of the lungs produced by silica dust). Sand, on the other hand, is low in initial cost, has the ability to absorb moisture, and gives to the work certain colors and finish which are difficult to obtain with steel abrasives.

*Blasting Equipment.* The equipment for blast cleaning consists of a storage tank, a heavy rubber hose for carrying the abrasive to the point of use, and a round nozzle which directs the abrasive material against the work being cleaned. Other equipment necessary for blast cleaning consists of a blast table and a blast room, or some type of enclosure in which the actual cleaning takes place.

Three types of blasting machines are used: barrel, table-room type, and full automatic.

**BARREL TYPE.** The barrel type of equipment consists of a tumbling barrel, in which sand or grit is introduced through nozzles placed at both ends of the barrel. This is the cheapest method of blasting and is used on small work. The method differs from *barrel finishing* in which the parts, usually small, are tumbled against each other and sometimes with other materials and possibly a lubricant for the purpose of burnishing, removing burrs, or cutting down sharp corners.

<sup>1</sup> By E. A. Reehl.

**TABLE-ROOM TYPE.** The table-room type of equipment consists of a revolving table and a blasting room. One-half of the table is outside the enclosure and the other half is within the room. Blasting is done by an operator on the inside of the room while an operator on the outside removes the finished work and reloads the table. This method is used on medium and large work such as stove castings, gears, and refrigerator evaporators.

**AUTOMATIC TYPE.** The automatic type of equipment consists of an endless belt conveyor running in an enclosure that is equipped with stationary and movable nozzles which blast the work as it moves along on the belt. This method is used extensively in the steel industry for cleaning billets, tubing, bars, sheets, plates, and pipes.

Blasting machines should be equipped with an efficient dust exhausting device so the operator may work in comfort and so he may see the work he is cleaning. The light in the sand-blast room should be good — equivalent to sunlight with no shadows falling on the work.

Three-eighths inch nozzles are almost universally used in blast cleaning, and an air pressure of about 70 to 80 lb per sq in. will be found to be quite efficient to clean most metal work and will be more economical than larger nozzles and higher air pressures.

**19.3. Pickling.<sup>1</sup>** Pickling is the treatment with an acid solution to remove all oxides, scale, or dirt. It is usually done to clean and brighten the surface, although sometimes deliberate etching may be required.

Since acids do not dissolve oil or grease, the work must be cleaned before pickling by a combination of the methods previously discussed. An alkaline cleaning method is usually used just previous to pickling.

An acid solution is selected dependent upon the base metal and the type of scale to be removed. Several examples are given below.

**Iron and Steel. Rust.** Rust is usually removed in a cold solution of one part muriatic acid and one part water.

**ANNEALING SCALE OR SCALE FROM HEAT TREATMENT OR WELDING.** Such scale is removed by either of the acid solutions given here.

- a. Hot sulphuric acid: 10 per cent sulphuric acid (by weight), 90 per cent water. Temperature 160 to 180 F.
- b. Muriatic acid: Cold — 1 part acid, 1 part water; Hot — 1 part acid, 3 parts water. Temperature 100 to 140 F.

With special steels or where the scale is difficult to remove, a mixture of acids is sometimes necessary. One mixture often used is the following: 1 gal water, 1 pt sulphuric acid, and 1.2 pt muriatic acid, at a temperature of 140 to 160 F.

<sup>1</sup> By F. A. Infield.

**SAND FROM CASTINGS.** This can be removed by a solution of 6 to 8 per cent hydrofluoric acid, temperature 140 to 160 F.

Any of the above solutions would etch iron or steel if it were left too long in the solution. To secure uniform pickling without etching or pitting, inhibitors are often used. An inhibitor is a substance, added to an acid solution, which permits the acid to attack oxide or scale but prevents it from attacking the clean base metal. Many commercial inhibitors are available which are very efficient with sulphuric acid. With muriatic acid, the inhibitors are not quite so efficient but are still very useful and have a number of applications.

TABLE 19.1. CONCENTRATIONS OF SEVERAL ACIDS USED IN PICKLING

<i>Oil of Vitriol</i> , commercial sulphuric acid ( $H_2SO_4$ )
Specific gravity, 1.84
93% actual $H_2SO_4$ , by weight
<i>Muriatic Acid</i> , commercial hydrochloric acid (HCl)
Specific gravity, 1.16
32% actual HCl, by weight
<i>Aqua Fortis</i> , commercial nitric acid ( $HNO_3$ )
Specific gravity, 1.38
60 to 62% actual $HNO_3$ , by weight
<i>Hydrofluoric Acid</i> (HF)
Specific gravity, 1.235
60% actual HF, by weight

After any of the above pickling methods, thorough rinsing is important. Iron or steel which is freshly pickled is very susceptible to rusting. Accordingly, after pickling, the work is quickly rinsed in cold running water. After this, a boiling water rinse, containing an alkaline neutralizer, is used, and the work is dried with an air blast. The alkaline neutralizer may be a solution of sal soda or borax ( $\frac{1}{2}$  oz per gal). This neutralizer prevents rusting for a short time. However, steel articles that have been pickled and that have to be stored or stocked for some time before assembly are often protected by the use of a slushing compound. A slushing compound is an oil, or a solution of an oil or grease in a suitable solvent. The work is immersed in this compound and drained, so that a thin film of oil or grease remains to exclude moisture and air and prevent rusting.

**DEOXIDINE AND METAL PREP.** These patented commercial preparations are solutions of phosphoric acid and higher alcohols (butyl and ethyl alcohols). They are used to prepare steel articles for lacquering or painting. The alcohols remove oil and grease, permitting the phosphoric acid to remove rust. After rinsing in cold water, then boiling

water, and finally drying, the steel surface is left in good condition for lacquering or painting.

*Copper and Brass.* (1) To remove oxide or scale a 10 per cent sulphuric acid solution is used, at a temperature of 140 to 180 F. (2) To brighten the base metal after removal of the oxides, the following cold solution is used: 1 gal nitric acid, 3 gal sulphuric acid, 1 qt water.

*Aluminum and Aluminum Alloys.* Aluminum is very soluble in most alkalies. (1) A weak alkaline cleaner is therefore used to remove all grease and dirt, and with aluminum this will dissolve oxides also. (2) After a cold water rinse, the parts may be brightened by a dip in a nitric acid solution, which is composed, by weight, of 15 per cent nitric acid and 85 per cent water.

Table 19.1 gives the concentrations of several acids used in pickling.

#### COATING OF METALS

**19.4. Electroplating.**<sup>1</sup> Electroplating may be described as a process in which metals are deposited or plated from solutions containing metallic ions by means of electrolysis. The main purposes of depositing one metal on another by electroplating methods are: (a) to afford protection against corrosion of the base metal, and (b) for decorative effect.

The technique of electroplating is basically the same for all metals, although there are certain variations in some of the details. The need for thorough cleaning of the parts to be plated is of fundamental importance; if the surface of the work is not chemically clean, the deposit will not adhere. Oil and grease are generally removed by immersing the parts in a hot alkaline cleaning solution. Although new improved solutions have been developed, a composition of caustic soda, soda ash, trisodium phosphate, and soap is frequently used. Sometimes the cleaning action is accelerated by using the electrocleaning method discussed in the section on alkaline cleaning. When the parts are freed from the last traces of oil and grease, they are rinsed in clean water, and if scale or oxide is present on the surface of the metal, it is removed by pickling in a suitable acid. Following the pickling process, the parts are again thoroughly rinsed in clean water and placed in the plating bath.

In the plating operation, the articles are connected electrically to the cathode bar, and on the anode bars are suspended slabs of the metal being deposited (see Fig. 19.1). The solution itself contains dissolved salts of the metal to be plated, and in order to increase its conductivity, other chemicals which will ionize highly are added. An example of this is the addition of sulphuric acid to an acid copper plating bath. Direct

<sup>1</sup> By W. L. Maucher.

current impressed on the system results in the migration of the metallic ions to the cathode and their deposition, upon losing their charge, as metal on the cathode.

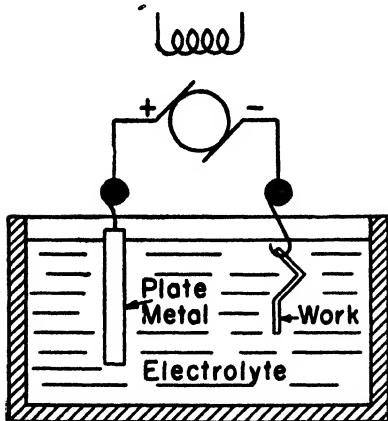


FIG. 19.1. Schematic diagram of the electroplating operation. The work is connected to the cathode, and the plate metal is the anode. Power is furnished by a d-c generator.

of plating solutions in the order of their ability to *throw* into recesses is given below.

- |                     |                               |
|---------------------|-------------------------------|
| 1. Alkaline tin.    | 5. Nickel (neutral solution). |
| 2. Cyanide cadmium. | 6. Acid copper.               |
| 3. Cyanide copper.  | 7. Acid zinc.                 |
| 4. Cyanide zinc.    | 8. Acid chromium.             |

If it is necessary or desirable to plate recessed parts with such metals as chromium, special anodes are used. These anodes are roughly similar in shape to the part to be plated, and are placed in position beside the part so that a more uniform spacing between anode and cathode is obtained. This special anode gives a more uniform current density over the part, resulting in a better plate in the recesses.

*Barrel Plating.* Small articles such as bolts, nuts, washers, and screws are usually plated by what is known as *barrel plating*. After cleaning, the parts are placed in a perforated drum or barrel fitted on the inside with suitable electrical conductors on which the parts slide as the drum is rotated mechanically in the plating bath. Articles are usually somewhat brighter than those plated in a still bath because of the burnishing action obtained while they are being tumbled in the drum.

*Throwing Power of Plating Solutions.* Operating conditions will vary with different types of electroplating. Some metals, such as cadmium, copper, and nickel, will deposit most satisfactorily with a low current density. Chromium, on the other hand, requires a high current density in order to obtain satisfactory results. The *throwing power* of electrolytes may be defined as their ability to electroplate or deposit metal in recesses. There is a large difference in the throwing power of different plating solutions, and this fact should be taken into account in designing parts to be electroplated. The throwing power

*Appearance.* Although cadmium and zinc coatings have found a wide use in protecting iron and steel from corrosion, they do have their limitations. Being comparatively soft metals and of the "reactive" type, they do not lend themselves to a high degree of polishing and will also discolor in time. Therefore, when both corrosion and appearance are primary considerations, nickel and chromium deposits are resorted to. Numerous household appliances and automobile parts are so plated. The so-called chromium plate is usually a composite plate of copper, nickel, and chromium. The first two metals are deposited to a total thickness of 0.0005 to 0.001 in., and after buffing the nickel, a thin electroplate of chromium is applied. The usual thickness is only 0.00003 in. In a system of this kind, the copper and nickel furnish the necessary protection to the base metal, while the chromium serves the twofold purpose of preventing tarnishing and imparting a very pleasing appearance to the article.

Parts plated with nickel and chromium and other hard metals are often polished to improve both the appearance and the corrosion resistance. Soft metals, such as cadmium and zinc, are not suitable for polishing, as stated previously.

*Costs of Plating.* In general, the cost of the plating metal is small compared with cleaning costs, labor costs, etc. Therefore, except where price difference between two metals is large, the costs for plating the different metals will be nearly equal. Differences in plating costs due to cost of the metal become of most importance when production of large quantities is considered.

Polishing adds considerably to the cost of plating, and therefore the advantages in improved appearance and corrosion resistance must be balanced against the increased cost.

**19.5. Calorizing.** Calorizing is the commercial name for the cementation of a metal surface by means of aluminum. The process is intended primarily as a means of protecting iron from oxidation at elevated temperatures rather than from the more familiar types of corrosion.

*Methods of Calorizing.* The method of calorizing as first developed consisted in packing the thoroughly cleaned parts in a drum filled with a mixture of powdered aluminum, aluminum oxide, and a small amount of ammonium chloride. The drum was slowly rotated as it was being heated, and an inert atmosphere, usually of hydrogen, was maintained within it. For steel and iron, a temperature of 900 to 950 C was recommended, and for copper and brass parts, 700 to 800 C.

A modification of this method consists in packing the cleaned metal in a drum as described above, and filling with a mixture of powdered

aluminum, powdered zinc, and ammonium chloride, the proportions being in the ratio of 4-1-1, respectively. The rotating drum is held for 3 hr at a temperature of 500 C for steel parts and 400 C for copper parts. No hydrogen is used in this process, since the zinc and ammonium chloride, when heated, produce reducing conditions within the drum. After removal from the drum, the parts are fired at 800 C for  $\frac{1}{2}$  hr. The coating produced by this method is relatively thin and will permit a reasonable amount of deformation without flaking off. It is not recommended for service temperatures over 800 C.

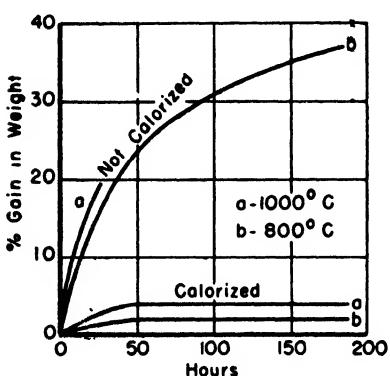


FIG. 19.2. Rate of oxidation (reported as per cent gain in weight) of calorized and uncalorized iron parts at two elevated temperatures.

ence in the rate of oxidation of iron in the treated and the untreated conditions, at 800 and 1000 C.

Most of the resistance to oxidation at high temperatures shown by a calorized metal can be attributed to the tenacious coating of aluminum oxide or alumina, which readily forms in the early stage of the heating and prevents further oxidation of the underlying metal. The calorized coating when first put on is relatively thin. Upon heating, however, the aluminum diffuses deeper into the metal, and the coating becomes thicker but, of necessity, of a lower average aluminum content. This fact is of importance as it limits the temperature at which calorized metals may be used to best advantage. If the outer protective layer of alumina becomes broken after the article has been used for a time, it cannot be renewed, as the aluminum content of the underlying layer has been lowered too much as a result of diffusion, and deterioration of the entire article will result in a short time.

The hot-dipping process is another modification which is now being used for protecting heater tubes and the other parts of mercury boilers which are exposed to high temperatures. In this process, the parts are thoroughly cleaned, fluxed in calcium chloride, and dipped in molten aluminum for about 20 min. They are then baked in a hydrogen atmosphere at 950 C for 24 hr.

*Protection Against Oxidation.* As was stated before, the calorizing treatment is especially recommended as a protection against oxidation at high temperatures. Fig. 19.2<sup>1</sup> shows the very decided differ-

<sup>1</sup> By W. E. Ruder.

According to one authority, the life of calorized iron below 900 C should be almost unlimited; if used at 900 to 980 C, the probable maximum life will be 20 times that of an untreated piece; while if the service temperature is from 980 to 1100 C, the life may be 5 times that of an untreated piece. G. H. Howe and G. R. Brophy also place 900 C as the maximum temperature to be used in order to obtain long life with calorized iron.

*Uses.* Calorized coatings have proved to be quite resistant to attack by sulphurous gases, and hence, such materials have found an important application in the oil refining industry, for parts such as tube stills, valves, retorts, and condenser parts. Other applications include furnace parts, such as conveyors, stokers, roasters, rotary driers, and kiln parts, carburizing and heat-treatment boxes, and pyrometric equipment.

**19.6. Galvanizing.** Galvanizing is a commercial term used to designate a process by which a zinc coating is produced on iron or steel by immersion in molten zinc. The expression *galvanized* had its origin in the concept of the galvanic (electrochemical) protection from corrosion afforded by zinc in contact with iron or steel.

*Hot-Dip Galvanizing.* The hot-dipping process for covering metal products with metal coatings is very simple in theory. The article to be coated is properly cleaned and then completely immersed in the hot metal and withdrawn with enough of the molten metal adhering as a surface film to give it the desired coat. The preliminary cleaning of the metal products to be coated, the fluxing of the surface of the bath of molten metal, and regulation of the bath temperature and the control of impurities are important factors, each of which has a bearing on the quality of the coating produced.

This process as practiced for the production of zinc coatings on irregularly shaped articles is entirely a manual operation. Such articles as structural shapes, castings, bolts, nuts, and fabricated parts, such as garbage pails, laundry tubs, and vats, are dipped by hand. The galvanizing of regular shaped materials, such as sheets, wire, and fencing, is done by means of automatic machines.

Like all processes of metal coating, the degree of success is dependent to a large extent on the cleaning of the surface of the metals prior to being coated. First, if the parts contain any oil, grease, or drawing lubricant, they must be thoroughly cleaned in a suitable degreasing solution, the type most frequently used being a boiling solution of alkaline compounds, such as caustic soda, soda ash, trisodium phosphate, and possibly soap. Following this, the parts are rinsed in water, and if any oxide or annealing scale is present, it is removed by pickling in an acid bath. A 7 per cent solution of sulphuric acid, maintained at a

temperature of 150 to 170 F is most commonly used. The time necessary for the complete removal of the oxide scale varies somewhat, and rather close inspection is necessary. For castings, dilute hydrofluoric acid is often used in conjunction with the other cleaning operations in order to remove the grains of sand adhering to the surface.

When the parts have been thoroughly cleaned, they are immersed in a flux which usually consists of a solution of zinc chloride and hydrochloric acid. In the hand dipping of pieces of irregular shape, the articles are thoroughly dried at this stage before being put into the molten zinc bath. In the zinc coating of wire, which is an automatic setup, the wire is passed through the flux and dried before passing on into the zinc. The adhering film of zinc chloride prevents any oxidation during drying and causes the zinc to flow uniformly on the articles.

The ordinary galvanizing bath used for coating steel sheets contains approximately 30 tons of molten zinc, and baths containing as much as 75 tons are not uncommon. The container, or "pot," is made either of open-hearth iron or of welded low-carbon steel. A coke fire was formerly used almost exclusively as a source of heat, but now gas is used considerably in this country. The length of time of immersion in the molten zinc depends upon the mass of the articles being coated, since it is necessary that the articles attain the temperature of the bath in order for adherent coatings to form. Therefore, large pieces must remain in the zinc considerably longer than small ones. The temperature of the bath varies somewhat with the type of work being processed, but the average is about 450 C.

Usually the surface of the molten zinc bath is divided in the center by means of a baffle, and ammonium chloride is spread on the surface of the section where the parts are immersed in order to give a final flux to the parts and to prevent the formation of oxide dross, which would contaminate the clean surfaces of the parts and prevent good adherence of the zinc. At the exit end of the bath, a flux covering is not generally used, and in the hand-dipping process, the surface is cleaned off with a wooden paddle just before the article is brought out. After hand dipping, the coated article, such as a tub, is turned upside down to allow all excess zinc to drain off; it may also be rapped sharply to aid in removing the excess zinc. Machines have been developed for removing the excess zinc from small articles such as nails and threaded parts, by shaking and centrifuging.

*Nature of Coating.* The coating produced by hot-dipping is far from being simply a layer of zinc spread over the surface of the steel because the molten zinc tends to dissolve the iron and steel in contact with it. A microscopic examination of a galvanized part reveals three distinct

layers. Adjacent to the iron is a layer of presumably  $\text{FeZn}_3$ , then an intermediate layer of  $\text{FeZn}_7$ , and on the outside a layer of zinc. The alloy layers comprise the larger part of the coating.

**Applications.** From the standpoint of corrosion, hot-dip galvanizing is one of the most widely used metallic coatings. It is used for all forms of outdoor hardware, structural parts, pipe, sheeting for roofs and walls of buildings, washtubs, ash cans, telegraph wire, fencing materials, transformer parts, transmission tower parts, and switchgear equipment.

**19.7. Phosphate Coatings.** These are coatings produced by converting the surface of iron or steel parts to an insoluble phosphate, such as iron phosphate or zinc-iron phosphate. Two popular types of these coatings are known as *Bonderizing* and *Parkerizing*.

Both types are applied in a similar manner. The parts to be processed are first degreased and cleaned free from oil, grease, rust, scale, etc., and then immersed in the processing solution, which is maintained at about 190 F. The Bonderizing solution will produce a coating in about 3 min, while the time for Parkerizing is about 45 min. Steel tanks heated with steam coils are used.

Bonderizing is applied primarily as a base for paint and lacquer coatings. While it does not have much resistance to corrosion in itself, it affords excellent adhesion for paints and prevents the spread of rust where the paint is scratched through to the base metal.

Parkerizing, being a heavier coating, provides reasonable corrosion protection for indoor use. However, it is essential that parts exposed to outdoor conditions be kept coated with a suitable rust-inhibiting oil or paint, otherwise rusting will ultimately occur.

**19.8. Black Oxide Coatings.** This type of coating is produced by converting the surface of iron or steel to black iron oxide ( $\text{Fe}_3\text{O}_4$ ) having a thickness of about 0.0001 in.

The process consists in immersing the cleaned iron or steel parts in a highly concentrated solution of salts, sold on the market under many trade names. The solution is strongly caustic and must be maintained at a temperature of 290 to 300 F to provide suitable coatings. The time of treatment is approximately 15 min.

In itself it affords limited corrosion protection, perhaps 5 to 8 hr in the salt spray, but it does produce a pleasing black color and it provides a good base for the application of rust-inhibiting oils. Its applications are limited primarily to indoor exposure where corrosion conditions are not severe.

**19.9. Other Coatings for Metals.** There are several other materials and methods of coating which are of importance for particular applica-

tions. Space does not permit discussing them in any detail, but a few of the more common ones are mentioned below.

*Metal Spraying or Metallizing.* In this process, the coating metal is melted (either in a gas flame or in a separate melting pot), then atomized by an air blast and deposited in atomized form on the surface to be coated. The method and some of its applications are discussed in Chapter XVI.

*Chromizing.* This process is similar to carburizing. Low-carbon steel parts are packed with a mixture of alumina and chromium powder and heated in a hydrogen atmosphere, forming a surface layer of chromized material of 10 to 20 per cent chromium, according to time and temperature of heating. The surface has good corrosion resistance (for oxidizing acids and atmospheric corrosion) and erosion resistance, and since it is nearly carbon free, there is no danger of carbide precipitation as with the high-chromium alloy steels. Turbine buckets have been protected by this process.

*Sherardizing.* The Sherardizing process consists in coating small parts with a layer of zinc by tumbling the parts with zinc dust in a sealed drum heated to 660 to 700 F for 3 to 12 hr, depending on the thickness of coating desired. The process is not widely used at present because the coating is filled with minute cracks (probably the result of differences in expansion on cooling), and the iron which diffuses into the coating, if greater than 15 per cent, causes a red rust color after relatively short exposure to the atmosphere. The other methods of zinc coating appear to be taking its place.

*Siliconizing.* In this process, iron and steel are impregnated with silicon for improving the surface resistance to corrosion, heat, and wear. Silicon-impregnated articles are resistant to nitric, sulphuric, and hydrochloric acids, decreasing in the order named. Resistance to scaling is good for long service up to 1200 to 1600 F. The surface is nongalling and seems well suited for applications requiring combined corrosion resistance and wear resistance.

#### ORGANIC FINISHES<sup>1</sup>

Organic finishing consists in coating a surface with a continuous film of an organic film-forming material. This film may be applied for the purpose of protecting the surface from corrosive influences, to enhance the appearance, or a combination of both.

**19.10. Organic Finishing Materials.** The organic finishes of industrial importance at the present time are as follows: asphaltic paints, oil paints and enamels, synthetic resin enamels, and lacquers.

<sup>1</sup> By E. A. Zahn.

*Asphaltic Paints.* The simplest asphaltic paint is one which is nothing more than a solution of asphalt in a suitable solvent, such as toluol or benzene. Such a paint when applied to a surface dries mainly by evaporation of the solvent. This leaves a coating which is identical with the asphaltic material from which the paint was made. Such paints afford a very convenient means of coating a surface with a uniform and thin film of asphaltic material which is very resistant to the attack of acid, alkali, and moisture, but it is readily attacked by oil or gasoline.

More complex asphaltic paints may contain, in addition to the asphaltic material, such ingredients as resins, drying oils, and pigments (see Chapter X). Paints made with such materials require baking at elevated temperatures after application to a surface. When applied properly, these materials afford a finish which is very resistant to corrosive influences.

*Oil Paints and Enamels.* The chief ingredient of an oil paint is a vegetable drying oil. These oils are mixed with suitable pigments and drying accelerators to produce oil paints. Oil paints, although they are used extensively for finishing houses, etc., have the disadvantage of slow drying. For some applications, this can be overcome by baking at an elevated temperature (about 300 F) for a short time. For industrial uses, oil paints have, for the most part, been replaced by synthetic resin enamels.

*Synthetic Resin Enamels.* Enamels of the synthetic resin type (see Chapter X) dry either by polymerization or a combination of polymerization and absorption of oxygen from the air. Both of these processes are greatly accelerated by the application of heat. It is, therefore, necessary to bake synthetic resin enamels at elevated temperatures to obtain maximum durability. It is possible, however, by the introduction of driers in the form of metallic resinate, etc., to produce quick air-drying enamels, thus extending the use of synthetic resin enamels to include applications where baking cannot be easily applied for other reasons.

*Lacquers.* High speed production, particularly in the automotive industry, created the demand for finishing materials which would dry more quickly than those which were available until about a decade ago. This demand was answered by the development of pyroxylin lacquers.<sup>1</sup> They dry by evaporation of the solvent, and since volatile solvents may be used, they dry quickly. They are the fastest drying organic finishing materials known.

The chief disadvantage of pyroxylin lacquers is their poor adhesion

<sup>1</sup> Solutions of pyroxylin, ground with suitable pigments and modified by the addition of plasticizers and resins, form the lacquers.

to metallic surfaces, making it advisable to apply a prime coat of an oil or synthetic resin type before applying the lacquer. On the other hand, lacquer finishes lend themselves to polishing much more readily than do other types of finishes. Although lacquer presents a pleasing appearance as applied to a surface, a smoother and glossier finish is obtained by rubbing and polishing. This is the practice followed in the automotive industry, where lacquer has not been superseded by synthetic baked enamels, although nearly all popular priced cars, or those representing the largest production, are now finished with baking synthetic enamels. A smaller number of coats is applied and there is no necessity for rubbing or polishing operations as these enamels have a natural high luster and are very smooth in appearance.

**19.11. Finishing Systems.** A finishing system consists of the material or group of materials applied to a surface to produce a desired result. It may be made of one, two, or more coats of material. Where one material will answer all requirements, such as adhesion to the surface, protection from corrosion, and appearance, that material constitutes a finishing system. However, it is often necessary to apply a material to the surface to provide the necessary adhesion and protection, and another to obtain the desired appearance. The first coat is then referred to as a prime coat, and the final coat as a finishing coat.

Besides giving good adhesion to the surface, the primary coat must provide a surface to which the finishing coat will adhere. Pigments which add to the corrosion resistance are used, but since their color gives an undesirable appearance, only sufficient pigment is used to make the surface microscopically rough.

The material used for a finishing coat must be of the desired color and gloss. In addition, it must possess enough adhesion to hold to the surface to which it is applied, and it should add to the protective qualities of the prime coat. Where a combination system of a baked prime coat and a lacquer top coat is used, the lacquer solvent action may destroy some wearing qualities of the baked primer.

**19.12. Application of Organic Finishing Materials.** Organic finishing can be divided into three steps: (1) surface preparation, (2) application of material, and (3) drying.

Since steel is the most common material used in industrial fabrication, the application of finishes will be discussed with reference to that type of surface.

**Surface Preparation.** The first step in the preparation of a surface for painting is thorough cleaning. It is essential that the surface be completely free from grease and rust. The methods previously mentioned may be applied for this purpose. Materials for cleaning which

remove both grease and rust are also available. These materials are mixtures of grease solvents and acid. Two materials of this type are known to industry as Deoxidine and Metal Prep.

In addition to cleaning the surface, it is sometimes advisable to treat the surface with specially prepared solutions which deposit an adherent coating of insoluble inorganic materials. These materials tend to impart a rough finish to the surface (pickling, blasting, and wire brushing also accomplish this purpose), and, after finishing, prevent rust creeping under the paint film at places where the paint has been damaged. Materials of this nature, in the form of Bonderizing and Parkerizing solutions, have proved of value in adding to the protecting qualities of paint systems.

*Application of Material.* Organic finishing materials may be applied by any method that will leave a continuous film of material over the surface. The most common method until a few years ago was brushing. This method has been replaced on most production work by spraying and dipping.

(1) *Spray Painting.* In spray painting, the paint is atomized, by means of air, and sprayed against the surface being painted. The material deposited on the surface flows out to form a thin uniform coating. Spray guns of various types are on the market for use in paint application. Although they vary somewhat in detail, the ultimate accomplishment is to mix the finishing material with a strong blast of air.

Suction feed is used for guns handling small quantities of material, and pressure feed is available for use where large quantities of paint are fed to the gun through a hose from a pressure tank. The paint and air may be mixed within the tip of the spray gun (internal mix), or the paint may be atomized at a point just outside the spray tip by streams of air from several jets (external mix). Both types are adjustable so that the proper mixture may be obtained for different types of paint. The guns can be operated by either hand or automatic control. In the latter, a mechanical or solenoid valve opens the needle of the spray gun by pushing air against a needle plunger.

Solvent or thinner must be added to the paint to obtain the proper viscosity or consistency for spraying. The proper consistency must be determined by actual trial. As the paint is deposited on the surface, it must be just fluid enough to flow out smoothly. The operator, after some experience, is able to tell whether or not the paint is being deposited in the proper condition. He must also be able to judge the thickness of the film, since too thick a film of the wet paint will cause runs, and some materials will not dry properly when applied in layers too thick.

The spray gun, held at a distance of about 8 in. from the surface, must be moved with a uniform motion in a plane parallel to the surface being coated. The average thickness of a spray coat of paint is about 0.001 in. When a thicker film is required, it is usually necessary to apply more than one coat.

Spray painting should be done, when possible, in a spray booth equipped with an exhaust fan, both for the protection of the operator from paint mist and solvent vapors and for the elimination of the fire hazards. Booths equipped with the water curtain feature are widely used as a further prevention against fire and for reclaiming the paint overspray. Solvents used for finishing materials are generally inflammable and must not be handled near open flames or sparks.

When a finish of first grade appearance is required, it is advisable to eliminate every possible source of dust. Such painting should be done in rooms in which the dust is filtered from the air. Clothing worn by operators should be watched as a source of lint, and the air used for the spray gun should be filtered.

(2) *Dipping.* Painting by dipping has found a definite place in industrial painting because it lends itself to automatic application and because it is the only method by which paint can be applied in a uniform film to some irregular surfaces. While spray painting is well adapted to finishing flat or regular surfaces, the method is not suitable for spraying material into the remote corners of some types of apparatus. Nor is spray painting economical for finishing small pieces, because the overspray would be great in proportion to the material deposited on the surface. More recent developments in dipping technique have made possible one-coat applications on large surfaces which are surprisingly free from paint runs.

In dipping, the object to be coated is immersed in a tank filled with the paint. For some paints, it is necessary to withdraw the parts slowly, whereas in others it is advisable to withdraw them quickly. The process may be carried out in any tank of suitable size. If a pigmented paint is being used, the tank should be equipped with a system for circulating the paint, to prevent settling of the pigment. The proper viscosity or consistency of the paint must be determined by trial and controlled regularly by the viscosity method. The thickness of coat which can be obtained without runs or sags depends on the viscosity of the paint. The object being coated should be dipped in such a position that all surfaces will drain properly. Where possible all visible surfaces should drain at approximately the same angle. Although it is theoretically possible to finish a surface by dipping without developing runs, in practice it is difficult, especially if the surface is irregular.

(3) *Flow Coating.* Objects which are too large for dipping or where only one side is to be painted may be finished by flow coating. The part is placed on a shallow drain pan which may contain from 20 to 50 gal of paint, depending on the size of the part. This paint is drawn from the bottom of the pan by a gear pump and is returned through a hose and open-end nozzle by which it is directed on the work. The paint is allowed to run down over the surface and that which does not adhere is collected in the pan and is repumped until the complete part is coated.

Flow painting is also used on objects which are not accessible with a spray gun or brush. It will reach into most any crevice or behind tubes similar to dip coating if properly applied. The coating is not as uniform as a properly sprayed coating, however, as there is a tendency for a thinner coat at the top drainage point. All paints do not flow satisfactorily, so a paint should be specially formulated for best results in flow coating.

*Drying.* After each coat of material is applied to a surface, it must be dried as required by the nature of the material. Air drying materials are allowed to remain at room temperature for the necessary length of time. Lacquers will dry in about  $\frac{1}{2}$  to 1 hr, while oil paints sometimes require 24 hr or more. Materials which require baking are placed in an oven or under a bank of radiant heat lamps a short time after application. Most synthetic resin enamels require about 1 hr at 300 F, while some of the asphaltic materials must be baked about 1 hr at 450 F. With certain types of finishing operations, radiant energy drying offers a saving through lower installation cost, lower power consumption, and possibly a shorter drying time.

**19.13. Finishing Cost.** Material costs for finishing are based on the cost of material to cover 1000 sq ft with a film 0.001 in. thick. This gives a more accurate basis for cost comparison between two finishing materials than actual costs per gallon, because finishing materials vary in coverage.

Although the actual coverage of a gallon of material must be determined by production trials, an accurate theoretical coverage can be calculated from the density of the deposited film, the weight of a gallon of material, and the per cent solid material in the paint.

Cost figures computed from the theoretical coverage are somewhat lower than those calculated from actual coverage, but the theoretical costs afford a sound basis for comparison of costs of two materials which have not been studied in production. The theoretical cost for a finishing material is about 50 per cent less than the actual cost for spray painting because of overspray, waste, and excessive film thickness.

Although it might be expected that the theoretical and actual cost figures would be approximately the same in dipping processes as in spraying, dipping has been found to be as much as 35 per cent more efficient than spraying. This is due to the absence of overspray and of excessive film thickness. Theoretical cost figures should therefore never be used to predict actual finishing costs.

A typical comparison of the cost of two finishing materials is given in Table 19.2. These data refer to the cost of two white lacquers which were proposed for use in the same application. Note that the actual paint cost is computed by multiplying the theoretical cost by two. The total cost would include such items as the cost of cleaning, and the labor cost, but these would be the same for either lacquer and so were omitted from the comparison.

TABLE 19.2. COMPARISON OF COSTS OF TWO LACQUERS

	<i>Lacquer No. 1</i>	<i>Lacquer No. 2</i>
Unthinned lacquer, per gallon	\$2.50	\$2.11
Thinner, per gallon	\$0.51	\$0.51
Thinned lacquer, per gallon	\$1.54	\$1.28
Coverage, gallons per 1000 sq ft per 0.001 in. thickness	4.29	3.62
Coverage, dollars per 1000 sq ft per 0.001 in. thickness	\$6.60	\$4.63
Surface area to be finished per 100 units, sq ft	1210	1210
Paint thickness, inch	0.0014	0.0014
Theoretical cost per 100 units	\$11.20	\$7.85
Actual cost per 100 units (theoretical cost $\times$ 2)	\$22.40	\$15.70
Saving per 100 units using No. 2		\$6.70

**19.14. Selection of Finish.** A paint used for decorative purposes only and installed indoors or in protected locations requires a finish that will properly adhere to the surface, will produce the necessary toughness and adhesion, and abrasion resistance and will have the required color and gloss to give the desired appearance. If a paint is to be installed in outdoor locations, some of the same qualifications as for indoor finishes are required, but the finish system must also be resistant to sunlight, moisture, abrasion, sand, dirt, rain, and changes in temperature. There also may be special applications where a paint which would stand all of these conditions might encounter additional attack from chemical fumes, thus requiring properties other than normally would be needed for outdoor application. Sometimes apparatus is installed underground in manholes where it may be subject to partial or complete immersion in water and may be contaminated from seepage. This

again requires a different paint from that which would be used for outdoor application. In outdoor application, sunlight is one of the main deteriorating factors, while in underground equipment, moisture and chemical resistance and electrolytic action are important.

Organic finishes are also used for many other specific applications. Some of these are: surface arc-over resistance; easy removal of weld spatter adjacent to a weld; finishes which can be welded through and after welding leave a protective coating; controlled resistance coating for corona control, finishes which will be resistant to insulating oils and other insulating compounds (see Chapter X); finishes which will withstand high temperature without deteriorating; finishes which will not affect the temperature rise of apparatus internally heated; and finishes which do not require baking for parts that will not withstand baking temperatures. No one organic finish will meet all these requirements. Neither will an organic finish best suited to withstand a particular destructive agent generally last indefinitely. This necessitates the use of various standard finishes for various applications, selected so as to make refinishing as easy as possible when it is required.

In selecting a finish system for a new application, it is desirable to consult an expert on the subject and place your requirements before him, giving him all the needed information so that he will be in a position to make his best recommendation. If a finish expert is not available, the same information could be obtained from the reliable paint companies.

### REVIEW QUESTIONS

1. What three general methods may be used for removing oil, grease, and buffing compounds from a metal surface? Which method is almost always used to clean parts for electroplating?
2. Why is the effectiveness of the vapor degreaser greater on heavy gage than on light gage material?
3. What is electrolytic cleaning? Should the part to be cleaned be the anode or the cathode?
4. What is the purpose of sand and grit blasting? Is there any difference between barrel blasting and barrel finishing (tumbling)?
5. What treatment must be used previous to pickling? What result is achieved by pickling?
6. Name two purposes of electroplating. What is the "throwing power" of an electrolyte? What does this mean with regard to the design of the part for a plating operation? How do tin, nickel, and chromium plating solutions compare in throwing power?
7. What is the purpose of the following operations for coating iron and steel, and how are they accomplished? Calorizing, galvanizing, phosphate coating, black oxide coating, Sherardizing, chromizing, and siliconizing.

8. What methods may be used to prepare a surface for an organic finish? How may organic finishes be applied? Will one type of paint be suitable for most all service conditions?

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